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Strategic Materials: Technologies to Reduce U.S. Import Vulnerability

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Foreword

This report presents the findings of OTA's assessment of *Strategic Materials: Technologies to Reduce U.S. Import Vulnerability.* The study was requested by the House Committee on Science and Technology and the Senate Committee on Commerce, Science, and Transportation.

The United States imports well over $1 billion worth of chromium, cobalt, manganese, and platinum group metals annually. Many of the uses of these metals are essential to the industrial economy and the national defense. The United States imports virtually all of its requirements for these metals; their production is highly concentrated in two regions of the world: the Soviet Union and southern Africa. The potential for interruption of supplies from these sources has heightened congressional interest in alternatives to continued import dependence.

This study assesses the technical alternatives to continued reliance on southern Africa and the U.S.S.R. for strategic metals. Promising opportunities for domestic and diversified foreign production and for conservation and substitution are identified for each metal. Technical, economic, and institutional barriers to the implementation of the alternatives are reviewed and governmental options to overcome those barriers are identified and analyzed.

We are grateful for the assistance of the project advisory panel, workshop participants, contractors, and the advice of many government agencies in the United States and Canada. As with all of our studies, however, the content of the report is the sole responsibility of the Office of Technology Assessment.

John H. Gibbons

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Director

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CHAPTER 1

Summary

Three nations, South Africa, Zaire, and the U.S.S.R., account for over half of the world's production of chromium, cobalt, manganese, and platinum group metals. These metals are essential in the production of high-temperature alloys, steel and stainless steel, industrial and automotive catalysts, electronics, and other applications that are critical to the U.S. economy and the national defense.

With minor exceptions, there is no domestic mine production of any of the four metals. The Government maintains a material stockpile but its contents are reserved for national security purposes only. As a result, the U.S. industrial economy is vulnerable to a variety of supply disruptions that may arise in times of peace. Disruptions of supply, such as the Canadian nickel strike in 1968 and the rebel interruptions of cobalt production in Zaire in 1978, can have a major impact on U.S. industries which must, in times of shortages, either compete for limited supplies of strategic metals or limit production of products that use strategic metals. Competition for supplies can result in price increases that may eventually be passed on to consumers, while reduction or cessation of production may result in loss of market share or permanent withdrawal from some markets, weakening the competitiveness of U.S. industries.

In the longer term, there are many technical alternatives that can provide more secure sources of supply, improve the prospects for conservation and recycling of strategic materials, or speed the acceptance of substitute materials that reduce the need for strategic materials.

Few of these technical alternatives can be implemented immediately on the occurrence of a supply disruption: some are near commercialization, others require further testing and evaluation, and still others are only in the research and development (R&D) stage. Nearly all of the alternatives must overcome substantial economic and institutional barriers before their full promise to reduce U.S. reliance on southern Africa and the U.S.S.R. for strategic materials can be realized.

Government actions to assure secure supplies of metals critical to the United States have been limited largely to reliance on the national defense stockpile to ensure the availability of materials required for national defense in time of war, leaving it to the free market to provide a diversity of suppliers for the industrial economy. These actions are appropriate for normal commerce and for periods of military conflict, but they are not intended to protect American industry from disruptions of the supply of chromium, cobalt, manganese, and platinum group metals that might occur as a result of political disturbances, strikes, changes in political ideology or other non-war-related factors affecting supplier nations.

There is no single generic approach to reduce materials import vulnerability—to be effective, different actions must be taken for each metal under consideration. An overall strategy to reduce U.S. reliance on uncertain sources of supply of strategic materials should be based on a combination of three technical approaches:

- increase the diversity of world supply of strategic metals through the development of promising deposits, both foreign and domestic, outside of southern Africa and the Soviet bloc and through exploration for new deposits of strategic materials;
- decrease demand for strategic metals through the implementation of improved manufacturing processes and recycling of strategic materials from scrap and waste; and
- identify and test substitute materials for current applications and develop new materials with reduced strategic material content for future applications.

There is a wide range of actions that the Government may draw from to implement some or all of these approaches. These actions vary in cost, degree of Government involvement, probability of success, and contribution to the overall strategy for reducing vulnerability. The actions include:

Collection and analysis of data and the dissemination of results to industry. Government already plays a key role in provision of essential information about strategic materials. An expanded role, including more emphasis on identification of foreign investment opportunities for U.S. firms abroad, sponsorship of a substitution information "bank," development of better data about domestic mineral occurrences, and periodic reexamination of trends in strategic materials recycling and conservation, would help Government policymakers adjust strategies to changing circumstances, and encourage private actions to reduce vulnerability.

Support for research and development and for mineral exploration. Implementation of any technical approach to reduce import vulnerability will assume a continuing R&D effort, most of which will continue to need Government support. Strategic materials R&D programs, decentralized among many agencies, need better coordination if common objectives, goals, and purposes are to be met.

Federal funding of strategic materials R&D in the areas of recycling, substitution, and advanced materials appears adequate to keep pace with the changing materials mix in the economy. In the area of mineral exploration, prospects for a major domestic discovery of one or more of these materials are not promising, but could possibly be enhanced through greater support of public and private exploration research, including basic research on geological theories of mineral occurrence, improved geophysical, geochemical, and drilling equipment, and more intense study of the resource potential of Federal lands.

Assistance for education and training. Advanced materials, now in their infancy, hold promise of altering the mix of basic materials used in many applications now dependent on strategic materials. International competition for supremacy in these emerging markets is strong, with some other countries, including Japan, placing greater emphasis than the United States on technical education and training of workers in these fields. Increased Government support to U.S. educational institutions in conjunction with the advanced materials industry may be needed to ensure the long-term competitiveness in these fields.

Development of alternative technologies and materials. In cases where the principal barrier to commercialization of a technology is the cost of demonstration and pre-commercial development, or where benefits arise from having the technology or material "on-the-shelf," the Government could support the construction and operation of demonstration plants or the testing and evaluation of substitute materials. This would reduce industry response time in an emergency.

Financial assistance for domestic industry. The economics of nearly all opportunities for domestic mineral development are discouraging to potential investors. If the benefits of domestic mineral production are desirable from the public's perspective, however, assistance could be provided in the form of subsidies, purchase commitments, loan guarantees, tax incentives or other Government financial aid. Such programs need not be limited to mineral production: processing of ores and metals, production of substitute materials, and operation of recycling facilities could also be encouraged by similar programs. Financial assistance programs could be expensive, however, so that their cost effectiveness, compared to other alternatives and to reliance on the free market, needs to be carefully considered.

Role of Government in reducing materials import vulnerability. The degree to which the Government should actively support activities to reduce materials import vulnerability ultimately depends on the perceptions of policymakers as to the degree of harm that could result from supply interruptions, the probability that such interruptions may occur, and the role policymakers see for the Government in dealings with the private sector. In addition, the effectiveness of the technical approaches that Government chooses to pursue depends, to some degree, on its commitment to their success and to the coordination of the approaches in a unified strategy directed toward reducing materials import vulnerability. The effectiveness of Federal policies also depends on establishing goals for strategic materials policy, identifying the most promising technical approaches to reduce vulnerability for priority materials, coordinating governmental actions, and encouraging industrial and academic activities in support of the technical approaches. In view of the multiplicity of Government activities that already affect the strategic materials issue and the long time required to implement most of the technical approaches, the Government would need a process for the periodic reevaluation of strategic materials objectives and of the effectiveness of programs implementing the technical approaches.

The following sections summarize the background to strategic materials issues and the most promising technical approaches to reduce the vulnerability of the United States to interruptions of supplies of strategic materials.

Introduction

The United States is well endowed with many natural resources. Timber, coal, water, and agricultural resources are the envy of the rest of the world. The endowment is not complete, however. The United States is dependent on foreign suppliers for many mineral resources. The Soviet Union and the nations of southern Africa are suppliers of many of the minerals and metals that the United States must import. Although in some cases these nations play only a limited role in the world supply of raw materials, for some materials they quite literally dominate the market.

Mine production of cobalt, chromium, manganese, and platinum group metals, all essential to defense and to the civilian economy, is concentrated in the Soviet Union and southern Africa (see map on pp. 8-9 for the worldwide distribution of mine production of these metals). Reliance on a potential adversary such as the Soviet Union for materials essential to defense and industry is an obvious area for concern. Nor is it certain that supplies from nations in southern Africa will continue without interruption: the division of nations on racial grounds, the role of Soviet influence and Cuban military involvement, the internal political division of key mineral-producing countries, and the vulnerability of mines and transportation systems to sabotage and guerrilla actions combine to raise questions about the reliability of mineral supplies, regardless of the good intentions or financial needs of the governments in power.

Dependence of the United States on a few nations of uncertain reliability for materials that are essential to many industrial and defense uses has heightened concern over materials and minerals policy in recent years. This concern is not new; since World War II U.S. policymakers have sought ways to reduce U.S. vulnerability to interruptions of supplies of strategic materials.

The most visible policy taken by the United States to guard against disruptions of supplies of strategic materials is the National Defense Stockpile (see box A). The objective of the stockpile is to support U.S. defense, industrial, and essential civilian requirements during a prolonged military conflict or declared national emergency. If properly stocked and maintained, the stockpile can be effective in coping with a disruption of supplies during a war or extended military conflict.

However, the defense stockpile does not protect, nor is it meant to protect, American industrial and other civilian consumers from

Box A.—The Strategic Materials Stockpile

For over four decades, the strategic and critical materials stockpile has been seen as a kind of insurance policy for safeguarding the United States against the effects of a supply emergency. The stockpile, however, is only intended to safeguard military, industrial, and essential civilian needs in times of war or declared national emergency, and is not a general-purpose source in an emergency.

First established in 1939, the stockpile was built up rapidly in the post-World War II and Korean War era, when the goal of the stockpile was to accumulate a 5-year supply of critical materials. Many of the materials now in the stockpile date from this period, and may be antiquated due to changes in material specifications. During the Vietnam War period, substantial amounts of stockpiled material were declared excess to stockpile needs and sold by successive administrations—a circumstance that led to charges that the stockpile was being used to keep metal prices stable during the Vietnam War. (Stockpile goals had been reduced from the initial 5 years to 3 years in 1958, and to 1 year in 1972, before being raised back to 3 years during the Ford Administration.)

In 1979, Congress reaffirmed its commitment to stockpiling through enactment of the Strategic and Critical Material Stockpiling Revision Act (Public Law 96-41). The law stated that the stockpile "should be sufficent to sustain the United States for a period of not less than 3 years in the event of a national emergency . . . " and "is to serve the interest of national defense only and is not to be used for economic or budgetary purposes." The 1979 law also established a stockpile transaction fund, under which materials can be purchased for the stockpile from sales of excess materials. At the time the law was passed, stockpile inventories in excess of the 3-year requirement were valued at $4.9 billion. Acquisition needs were estimated to be $12.9 billion. In March 1981, President Reagan announced a major new stockpile acquisition program, aimed at meeting stockpile goals for 15 priority materials. For fiscal year 1985, the Administration is seeking to sell $78 million in excess materials and to purchase $120 million for the stockpile. However, the request is significantly below the amount required to meet stockpile goals. At present spending rates, it would take 100 years to meet stockpile goals.

The Federal Emergency Management Agency (FEMA) oversees the stockpile, and submits to Congress the Annual Materials Plan (AMP) for the buying and selling of materials for the stockpile. An AMP steering committee, comprised of 12 agencies and chaired by FEMA, develops the annual plan. Actual management of the stockpile sites, which are dispersed throughout the United States, is conducted by the General Services Administration.

Alternatives to acquisition and sale of stockpile materials are under consideration, including the potential for technology to upgrade stockpiled materials to today's standards. For example, most of the cobalt in the stockpile does not meet current industry requirements, and therefore may need replacement. The American Society of Metals, in a recent report to FEMA, suggested that U.S. firms be given stockpile samples to demonstrate whether the out-of-date materials could be processed to meet current standards. If so, some materials already in the stockpile could be readied for use in an emergency, and some materials may not need to be replaced through purchase.

Barter is an alternative means of obtaining materials for the stockpile. The U.S. Government operated a barter program under the Department of Agriculture from 1950 to 1973, which disposed of surplus agricultural commodities and acquired strategic materials for the stockpile. The total value of agricultural exports under this program was $6.65 billion. The barter program was suspended in 1973 when agricultural surpluses were drawn down, and stockpile goals were changed. In 1981, the U.S. Government again became involved in barter on a limited basis when it concluded three Jamaica bauxite-dairy barter agreements worth $47 million, but a formal barter program has not been reestablished. Approximately 20 barter bills have been introduced in the 98th Congress. The Administration has established a working group on barter to review proposals on a case-by-case basis.

Table A.—Domestic Consumption and Production of Strategic Metals

	Apparent consumption[a]	Domestic production		Price	
		primary	scrap		
Chromium:		(tons × 1,000)		$/M.T.[b]	
1979	586	0	67	54-58	
1980	567	0	72	54-58	
1981	533	0	70	51-55	
1982	333	0	63	48-52	
1983	334	0	78	48-52	
Cobalt:		(pounds × 1,000)		$/pound	
1979	18,806	0	1,170	24.58	
1980	17,054	0	1,183	25.00	
1981	12,532	0	972	19.73	
1982	11,452	0	871	12.90	
1983	15,712	0	724	12.50	
Manganese:		(tons × 1,000)		$/LTU[c]	
1979	1,250	31	0	1.40	
1980	1,029	23	0	1.70	
1981	1,027	24	0	1.72	
1982	672	4	0	1.58	
1983	730	4	0	NA	
Platinum group				$/troy ounce	
metals:		(troy oz × 1,000)		Platinum	Palladium
1979	2,992	9	309	352	113
1980	2,846	3	331	439	214
1981	2,445	7	392	475	130
1982	1,822	9	344	475	110
1983	2,464	9	287	475	130

[a] Apparent consumption equals total imports minus exports plus domestic production plus increases of stocks and inventories.

[b] Chromium price is for metric tonnes of Transvaal ore, f.o.b. South Africa.

[c] LTU (long ton unit) is the metal content of one long ton of one percent grade ore. It is equivalent to 22.4 pounds of contained metal.

NA—not available.

SOURCE: U.S. Department of the Interior, Bureau of Mines.

supply disruptions that result from economic or foreign political disturbances. The concentration of supply of important minerals in a few countries, combined with anxieties aroused by the success of the oil producers' cartel in the 1970s, has led to calls for materials policies that protect the Nation against supply disruptions in a wider range of scenarios than those contemplated under Defense Stockpile policies.

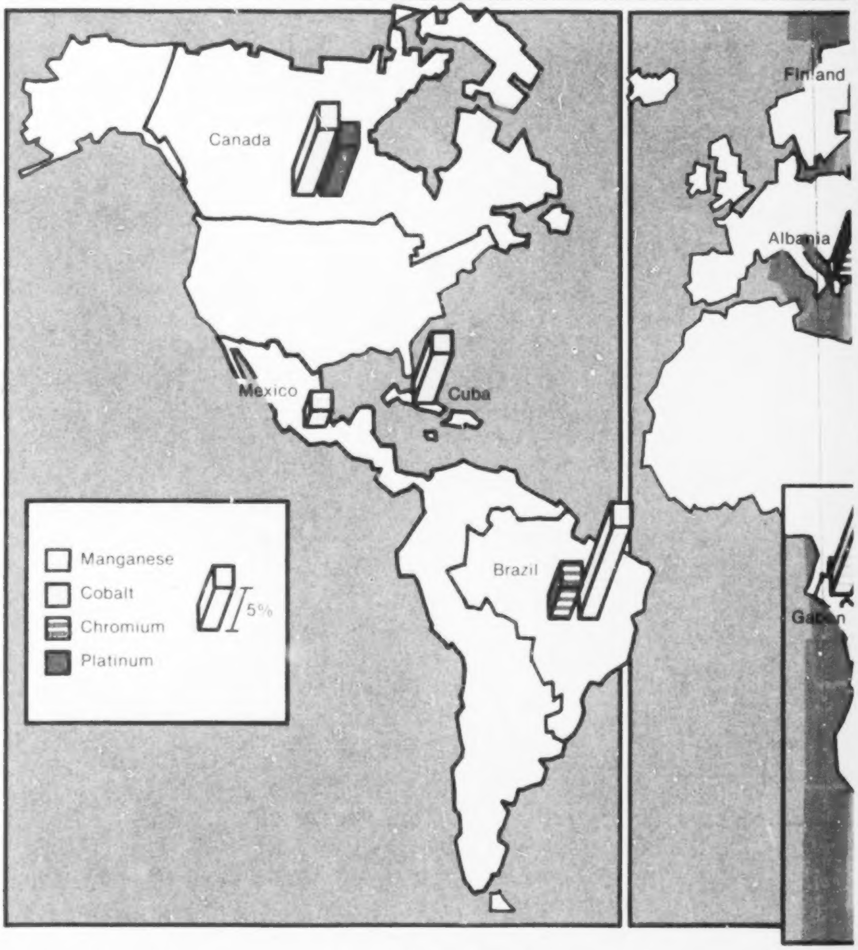
Two general approaches have been proposed to reduce materials import vulnerability in nonwar scenarios. One is to establish an economic stockpile, similar to the defense stockpile, but which may be used in times of economic disruption rather than military conflict. The purpose of such a stockpile would be to reduce the impacts to the U.S. economy from peacetime market and supply disruptions. However, there is considerable skepticism on the part of industry that an economic stockpile could be managed without causing market disruptions itself. The advantages and disadvantages of various types of economic stockpiles have been the subject of much study. (See, e.g., OTA's, *An Assessment of Alternative Economic Stockpiling Policies*, OTA-M-36, August 1976.)

The second approach is technological. Through a combination of technical advances in mineral production, conservation, and materials substitution, the requirements for imported strategic materials can be lessened and the reliability of supplies can be increased.

This assessment concentrates on the role of technology in reducing the vulnerability of the United States to interruptions of supply of strategic materials. The technical approaches may be directed either toward developing alternative sources of supply and alternative technologies for use in cases of supply interruption or, in the longer term, toward developing new materials and processes that significantly re-

Distribution of Mine Production of Cobalt, Chrom

Country	Material	Share
Canada	Cobalt	8%
	PGM	6%
Cuba	Cobalt	6%
Mexico	Manganese	2%
Brazil	Chromium	4%
	Manganese	11%
Finland	Chromium	4%
	Cobalt	3%
USSR	Chromium	33%
	Cobalt	8%
	Manganese	32%
	PGM	49%
Albania	Chromium	5%
Turkey	Chromium	6%
China	Manganese	6%
India	Chromium	3%
	Manganese	6%
Philippines	Chromium	5%
	Cobalt	4%
Australia	Cobalt	5%
	Manganese	8%


Canada
Mexico
Cuba
Brazil
Finland
Albania
Gabon
☐ Manganese
☐ Cobalt
▤ Chromium
■ Platinum
5%

SOURCE: Office of Technology Assessment, from U.S. Bureau of Mines data.

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ium, Manganese and Platinum Group Metals—1981

Zaire		
	Cobalt	47%
Gabon		
	Manganese	9%
Botswana		
	Cobalt	1%
Zambia		
	Cobalt	15%
South Africa		
	Chromium	34%
	Manganese	23%
	PGM	44%
Zimbabwe		
	Chromium	5%

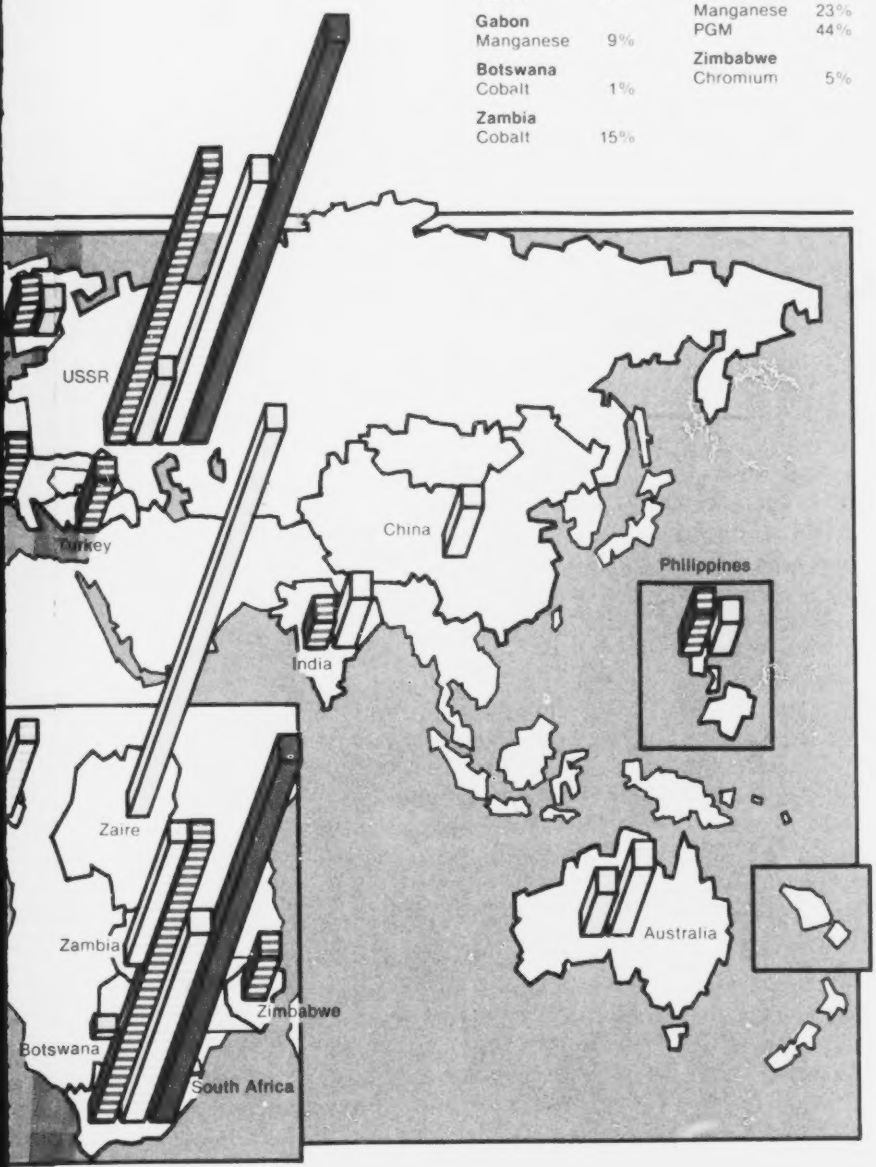
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Table B.—U.S. Imports of Strategic Materials—1982[a]

Source	Chromium		Cobalt		Manganese		Platinum group metals		Total value of imports ($ × 1,000)
	Amount (st. tons)	Value ($× 1,000)	Amount (th. pounds)	Value ($ × 1,000)	Amount (st. tons)	Value ($ × 1,000)	Amount (troy ozs.)	Value ($ × 1,000)	
Albania	1,360	299	—	—	—	—	—	—	299
Australia	—	—	169	1,305	23,601	4,647	4,766	1,567	7,519
Belgium/Luxembourg	—	—	613	6,402	—	—	107,017	23,121	29,523
Botswana	—	—	364	2,817	—	—	—	—	2,817
Brazil	9,219	6,932	—	—	26,569	9,197	—	—	16,129
Canada	311	240	1,483	14,404	15,975	5,822	95,326	18,774	39,240
China	3,613	2,672	—	—	—	—	—	—	2,672
Finland	9,520	2,206	798	10,423	—	—	5,988	2,182	14,811
France	—	—	336	3,202	80,729	35,710	—	—	38,912
Gabon	—	—	—	—	23,156	3,514	—	—	3,514
West Germany	2,622	3,926	255	3,082	1,031	691	30,863	6,595	14,294
India	—	—	—	—	7,204	2,646	—	—	2,646
Italy	346	607	—	—	—	—	27,719	6,855	7,462
Japan	165	347	1,024	8,771	4,564	3,334	3,546	1,383	13,835
Madagascar	12,920	2,683	—	—	—	—	—	—	2,683
Mexico	—	—	—	—	28,892	14,211	162,311	5,645	19,856
Netherlands	—	—	28	659	—	—	27,336	3,916	4,575
Norway	55	110	852	9,053	907	965	26,874	6,033	16,161
Pakistan	1,360	330	—	—	—	—	—	—	330
Philippines	15,652	5,830	—	—	—	—	—	—	5,830
Portugal	—	—	—	—	14,966	5,201	—	—	5,201
South Africa	113,473	40,996	266	1,127	246,584	78,438	1,194,564	355,356	475,917
Sweden	3,045	4,954	—	—	—	—	—	—	4,954
Turkey	12,649	4,947	—	—	—	—	—	—	4,947
United Kingdom	15	22	271	2,109	12,585	4,245	338,562	68,572	74,948
U.S.S.R.	8,840	1,629	—	—	—	—	405,043	37,733	39,362
Yugoslavia	10,153	8,144	—	—	2,998	1,063	—	—	9,207
Zaire	—	—	4,972	68,704	—	—	—	—	68,704
Zambia	—	—	1,164	11,323	—	—	—	—	11,323
Zimbabwe	21,576	20,290	—	—	—	—	—	—	20,290
Other	—	—	276	4,033	4,996	968	63,791	16,025	21,026
Total	226,894	107,164	12,870	147,414	494,757	170,652	2,493,706	553,757	978,987

[a] Amounts and Total Value depressed in 1982 because of the recession. Total value of imports was $1.6 billion in 1981 and significantly over $1 billion in 1983, although precise figures have not yet been published for that year.

SOURCE: U.S. Department of the Interior, Bureau of Mines.

duce the need for strategic materials. The various technological approaches identified are distinct from, but may be combined with, the nontechnical alternatives, that is, continuation of the current policy of supporting the defense stockpile and, potentially, the establishment of an economic stockpile.

Identification of Strategic Resources

What makes a material strategic? Two factors must be considered: the critical nature of its uses and the vulnerability of its supply. The criticality of a material is measured by its degree of use in applications essential to the United States, both civilian and military. Vulnerability is assessed on the basis of the risk that the supply of the material may be interrupted, and the scale and duration of the potential interruption. Thus, a strategic material may be briefly defined as follows:

> A strategic material is one for which the quantity required for essential civilian and military uses exceeds the reasonably secure domestic and foreign supplies, and for which acceptable substitutes are not available within a reasonable period of time.

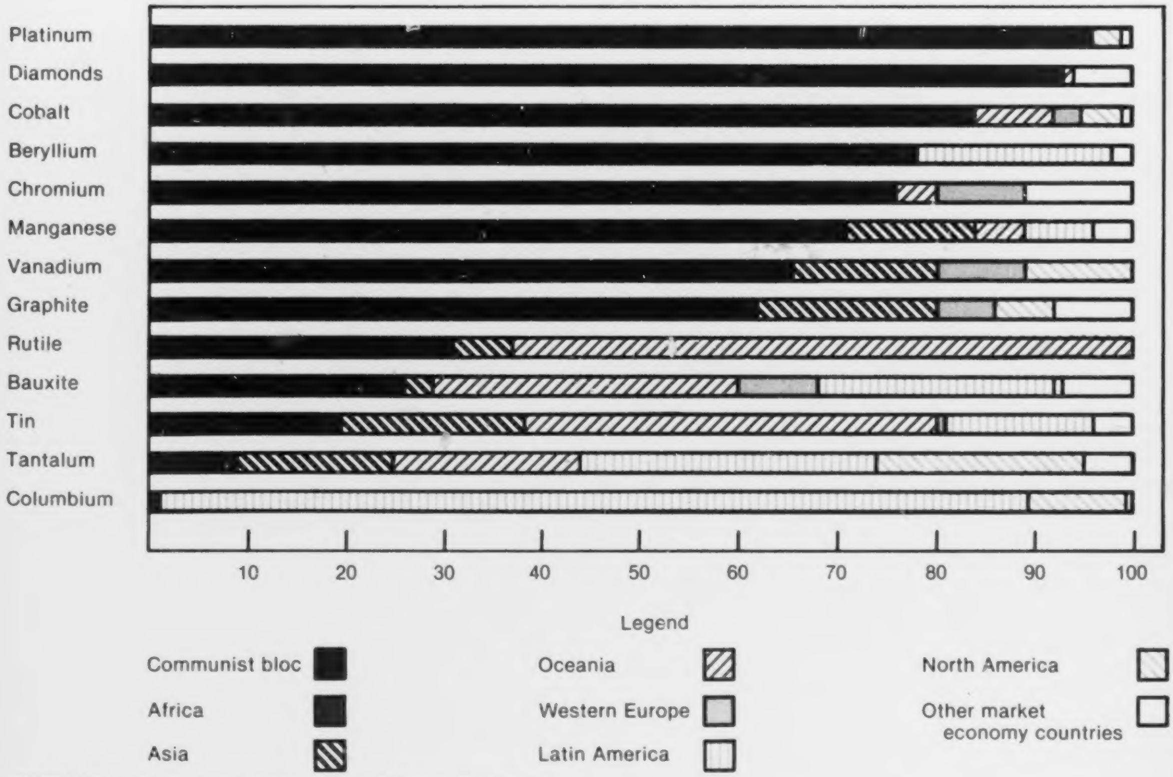
Because many materials are essential in some applications but not others, difficulties may arise in defining a material as critical. Definition of vulnerability poses still more difficulties, since the assessment of the risk of supply interruption involves a subjective analysis of the behavior of other nations. Altogether, the definition of a "strategic material," combining uncertainties both of criticality and of vulnerability is not a cut-and-dried matter.

The U.S. Bureau of Mines compiles and reports data on 86 important non-fuel mineral commodities. After eliminating the materials and minerals that the United States exports or for which the United States has no net imports and the minerals for which the United States relies on Canada for its supply, 33 commodities remain. This list can be reduced further by eliminating the materials which have a high degree of geographical and political diversity in their production.

The result is a list of 13 minerals and materials that are essential to the national economy and whose supply is relatively limited and vulnerable to interruption. The regional distribution of the production of these 13 strategic materials is shown in figure 1-1. For six of the materials in the figure, beryllium, chromium, cobalt, industrial diamonds, manganese, and platinum group metals, over 70 percent of world production is located in Africa or the Communist bloc. The pervasive role of chromium, cobalt, manganese, and platinum in the economy, as contrasted to the more limited roles for beryllium and industrial diamonds, place these four materials in a "first tier" of strategic materials; the remaining nine, while all essential to the U.S. economy, form a second tier of strategic materials.

The four first-tier strategic materials are the subject of this report. Chromium, cobalt, manganese, and platinum group metals are clearly essential to the United States, and their uninterrupted supply is certainly open to question. Issues considered with regard to these materials, and the technologies that may help reduce U.S. vulnerability to disruptions in their supply, will also have some application to materials in the second tier.

Figure 1-1.—Regional Distribution of Strategic Material Production



SOURCE: Office of Technology Assessment from U.S. Bureau of Mines data.

Essential Uses of Strategic Materials

The first-tier strategic materials have many uses, a number of which are considered to be essential. The essential uses of the first-tier strategic materials are discussed below.

Chromium

Chromium is used in a variety of applications throughout the economy, the most essential of which are superalloys, stainless steel, and as an alloying element in tool, spring, and bearing steels.

As an alloying element, chromium raises the hardness of steel, increases its strength and oxidation resistance at elevated temperatures, and increases its wear resistance. These properties make chromium alloy steel essential in springs, bearings, and tools, as well as in components of automobile engines.

In stainless steel, the formation of a tenacious chromium oxide film on the surface of the material provides a barrier to corrosion and oxidation. This corrosion and oxidation resistance is essential in chemical processing plants, oil and gas production, power generation, and in automobile exhaust systems, principally in the catalytic converter.

Chromium is combined with nickel, cobalt, aluminum, and titanium to give superalloys their exceptional corrosion and oxidation resistance at temperatures above the useful range of steel. For example, superalloys are used in the high-temperature regions of the aircraft gas turbine engine in parts such as turbine blades and vanes, turbine disks, and combustor liners.

Chromium in its mineral form of chromite is used in insulating liners in boiler fireboxes, steel and ferroalloy furnaces and vessels, and in foundry sands used for casting molds. In a chemical form it is used in pigments, metal treatments, leather tanning, and a variety of other applications. Although some of these uses are essential, the quantity of chromium required to meet them is small relative to the amount consumed in metallurgical applications.

Cobalt

Although U.S. demand for cobalt is less than 2 percent (by tonnage) of that for chromium, it is essential in many of its applications. The most critical are as an additive in some superalloys, as a binder for tungsten carbide tool bits, and as a constituent of some magnetic alloys. It is also desirable, but not irreplaceable, as an alloying element in some tool steels, hard facing alloys, and high-strength steels. Cobalt is contained in catalysts used in certain essential steps in the refining of petroleum and the manufacturing of chemicals. Other nonmetallurgical applications include pigments and paint dryers, but only a very small portion of these applications are essential.

Manganese

Although manganese is used in a variety of applications, ranging from an alloying agent in aluminum alloys and bronzes to nonmetallurgical uses in batteries and chemicals, its principal use—about 90 percent—is as an alloying and processing agent in steel. As an alloying element, manganese prevents the formation of iron sulfides which adversely affect the properties of steel. In addition, manganese is the most cost-effective method of increasing the hardness of steel, leading to its use in certain impact-resistant steels and in the high-strength low alloy (HSLA) steels. As a processing agent in steelmaking, manganese is instrumental in removing oxygen from steel and in improving slag characteristics.

Platinum Group Metals

Platinum group metals (PGMs), which comprise platinum, palladium, rhodium, iridium, osmium, and ruthenium, are essential in catalytic applications in petroleum refining, chemical processing, and automotive exhaust treatment. They are also used as contacts in telecommunication switching systems and as electrodes in ceramic capacitors, but in many of these applications gold is a satisfactory, albeit expensive, substitute for some of the platinum group metals. Other applications include jewelry and medical and dental equipment.

Outlook for the Future

Domestic production of stainless and alloy steel accounted for 237,000 tons of chromium in 1981. Requirements for these steels are projected to grow substantially for the rest of the century. Superalloys, which require high purity chromium metal or low carbon ferrochromium, accounted for less than 7,000 tons of chromium in 1981. Demand for chromium in this application may nearly double by the year 2000.

Domestic cobalt consumption was 5,800 tons in 1981. Superalloys, the largest consumer, accounted for 2,100 tons or 36 percent of domestic consumption. Magnetic alloys used about 800 tons (14 percent of domestic consumption); chemical and petroleum catalysts accounted for about 600 tons (10 percent of domestic consumption); and cemented carbide tools and dies consumed about 500 tons (almost 9 percent of domestic consumption). Growth of cobalt demand is expected to be slow over the next decade, increasing somewhat after 1995.

In 1981, 775,000 tons of manganese contained in ore and ferroalloys were used in the production of carbon, stainless and alloy steel. If current steelmaking practices continue, manganese requirements for the domestic production of steel would be expected to rise significantly. However, changes in steelmaking practices could result in a significant decrease in the amount of manganese required per unit of steel production, causing a major drop in future manganese consumption per ton of steel (see p. 27).

U.S. demand for platinum group metals was 1.92 million troy ounces in 1981. Of this total, 607,000 troy ounces, or 32 percent, were used in catalytic converters of automobiles. Other catalytic uses in the chemical and petroleum industries accounted for 342,000 troy ounces (18 percent of domestic consumption). Electrical applications accounted for almost 500,000 troy ounces (26 percent of domestic consumption).

PGM demand for catalytic converters may more than double by 1995 as automobile sales increase and as larger vehicles, such as heavy trucks and buses, are required to use converters. Demand for PGMs in the petroleum industry will probably grow at roughly the same rate as the economy, unless there is a sharp increase in demand for domestic fuels that would require large quantities of PGM catalysts in the expansion of refinery capacity. Growth of demand for PGM catalysts in the chemical industry is difficult to predict. Increased demand for "specialty" chemicals (e.g., pharmaceuticals, agricultural pesticides and herbicides, and biocatalysts) could push PGM consumption in the chemical industry to as much as 400,000 troy ounces in 1990 and to over 800,000 troy ounces by 2000. PGM demand in the electrical industry is likely to increase slowly, although a sharp increase in palladium demand for ceramic capacitors is likely in the near future and demand for this use will remain high for several years until high prices and tight supplies encourage the use of substitute materials in this application.

These projections must be taken with caution. They are based on extensions of current patterns and trends, and do not fully reflect the effects of advances in materials production technology, nor do they reflect technical advances in end uses that may result in significant increases or decreases in consumption of these materials. However, the projections do provide a starting point for the evaluation of the importance of the various technical alternatives to materials import reliance that are discussed below.

Production of Strategic Materials

Chromium is found in many parts of the world, but world mine production is dominated by several large, high-grade deposits. In 1982, South Africa accounted for 27 percent of the total world chromium production of about 2.6 million short tons. The Soviet Union produced 36 percent of the world total; six other countries, Albania, Brazil, Finland, the Philippines, Turkey, and Zimbabwe, each accounted for between about 3.6 and 6 percent of world production.

In 1982, the United States imported 227,000 short tons of chromium contained in ore and metal. About half of the imports were as chromite ore: 59 percent from South Africa, 6 percent from the Soviet Union, 11 percent from the Philippines, and the rest from a variety of sources. The rest of chromium imports were ferrochromium and chromium metal, with 35 percent coming from South Africa, 26 percent from Zimbabwe, 12 percent from Yugoslavia (produced, in part, from Albanian chromite), and the balance from diverse sources.

In 1982, Zaire produced 45 percent of the world supply of cobalt, while neighboring Zambia produced 13 percent. The Soviet Union and Cuba together produced 15 percent of the world's cobalt. Canada accounted for 6 percent and Australia 8.7 percent, with lesser amounts being produced in Finland, Morocco, the

Philippines, New Caledonia, and Botswana. Principal suppliers to the United States were Zaire, 36 percent of imports; Zambia, 8.5 percent; Canada, Norway, Finland, and Japan between 6 and 11 percent each; and Belgium/Luxembourg, 4.5 percent. Belgian cobalt originated from ore obtained from Zaire, while Australia, Canada, and the Philippines supplied cobalt ore to other processers.

Manganese ore supplies are more diversified among major producers than are supplies of chromium or cobalt. The Soviet Union accounted for 41 percent of 1982 world production and South Africa accounted for 23 percent. Australia, Brazil, Gabon, India, and China each accounted for between 5 and 7.1 percent. U.S. imports of ore came from Gabon (19 percent), South Africa (55 percent), Australia (16 percent), and Brazil (3 percent). Manganese was also imported as ferromanganese, with South Africa providing 40 percent and France providing 21 percent.

Production of platinum group metals is concentrated in the Soviet Union and in South Africa, accounting for 54 percent and 40 percent of 1982 world production, respectively. U.S. imports were from South Africa (48 percent), the Soviet Union (16 percent), and the United Kingdom (14 percent, processed from material imported into the United Kingdom from South Africa and Canada).

Historical Perspective

In the past 25 years, the United States has had at least four major disruptions in the supply of materials critical to the economy and the national defense. The first of these occurred in 1949 when, in a Cold War exchange of trade restrictions with the United States, the Soviet Union stopped the export of manganese and chromium ore to the United States. The second interruption was the U.S. boycott of chromium from Rhodesia (now Zimbabwe). The third was a many month hiatus in the import of nickel from Canada as workers carried on a prolonged strike. Most recently, political disturbances in Zaire, while not actually reducing cobalt production, triggered major disruptions in supplies, inventories, and prices for cobalt.

The Soviet Union embargo on chromium and manganese exports to the United States in 1949 was a political action. It was a response to a U.S. clampdown on exports of machinery, tools, trucks, and scientific equipment to the Soviet Union—which, in turn, was a response to the Soviet blockade of Berlin in 1948. Another politically motivated supply cutoff was the embargo on imports of Rhodesian chromium from 1966 to the end of 1971. The U.S. embargo conformed with a United Nations resolution which called on all members to refrain from trade with Rhodesia after it declared independence from Great Britain and set a course of continued white minority rule.

In neither of these cases were there serious effects on the economy or any interruption of defense production. The response in both instances was, essentially, to find other foreign sources of supply. After the 1949 Soviet embargo, the U.S. Government was active in finding alternative suppliers and in upgrading the infrastructure of these suppliers by providing steel to improve India's rail transport system, sending railcars to South Africa, and helping to improve rail and port equipment in Ghana.

With the U.S. embargo on purchases of Rhodesian chromium in 1966, the Government sold excess chromium from the national stockpile but otherwise took little active part, leaving industry to find alternate suppliers. That industry was able to do so quite readily with little evidence of shortage was due to several factors, besides the stockpile sales. The Soviets promptly volunteered to serve as alternate suppliers of chromium to the United States, even though the United States was fighting against their allies in Vietnam. Prices rose, drawing other suppliers like Turkey and the Philippines into increased production. And the Rhodesian embargo leaked. Despite the international embargo, France, Japan, and Switzerland bought what was probably Rhodesian chromium from South Africa and Mozambique. Had they not done so, the alternate suppliers might have been hard put to provide the whole industrialized world with chromium.

A most important factor in reducing the economic impact of the loss of Rhodesian chromium was the wide-scale adoption of the argon-oxygen decarburization process for the manufacture of stainless steel. This process made it possible to use high-carbon ferrochromium made from South African chromite in place of the more costly low-carbon ferrochromium made from Rhodesian ore that had been used before the embargo.

The 1969 nickel strike in Canada shut down supplies from the quintessentially "safe" foreign source. Unlike the politically inspired embargoes described above, it caused actual shortages and acute price hikes. The reasons for the acute effects were twofold: the cutoff occurred at a time of strong demand for nickel when world supplies had already been tight for 3 years; and Canada was then almost the sole supplier to the United States. Even so, military and essential civilian production continued without interruption throughout the shortage. By 1970, world nickel prices were back to normal and supplies were ample.

The shortages and high prices elicited changes in the behavior of U.S. nickel users. They substituted other materials where they could, for example, replacing nickel stainless steel with chrome-manganese stainless steel (a substitute alloy that had been developed during the Korean war). Many users turned to nickel recycled from scrap. And they paid high prices for the limited remaining supplies of nickel—once more supplied largely by the Soviets. An important factor in recovering from the acute nickel shortage was the U.S. Government's release of a large quantity of nickel from the stockpile as the strike came to its end. Earlier Government actions had been to allocate available supplies to military users.

During the cobalt "shortage" of 1978-79, there was never any real interruption of supply. On the contrary, production in Zaire and Zambia—by far the largest cobalt producers in the world market—rose 43 percent during 1978 and another 12 percent in 1979. But the combination of rapidly rising world demand and fears of a supply cutoff, triggered by a rebel invasion of Zaire's mining region, set off a wave of panic buying. This, coupled with the recent removal of an important source of world supply (sales from the U.S. stockpile) and the relatively low industry inventories of cobalt, sent cobalt prices soaring.

During the "shortage," cobalt users turned quickly to substitutions and recycling. Under the spur of high prices, nonessential uses made way for essential. Government allocation was not needed to reserve cobalt for superalloys for military jet engines; superalloy producers and users paid the high prices demanded by dealers, and they recycled. Use of cobalt in permanent magnets for loudspeakers dropped by half as ceramic magnets were substituted. The ceramic magnet technology was already on the shelf but had not been widely adopted because it required redesign and retooling. High cobalt prices made these changes worthwhile. The drop in demand for cobalt due to substitution, recycling and conservation had its effect on prices, which turned down in 1980. By 1982, with worldwide recession, cobalt prices plunged below the 1978 level.

None of these cases resulted in severe or long-lasting damage to the United States. Nonetheless, the issue of foreign dependence for materials critical to the country is a major one. For some materials, alternative suppliers are by no means as readily available today as they were in past years. In 1949, small producers such as India and Turkey were capable of expanding their production sufficiently to replace our major suppliers of manganese and chromium; they are not today. Nor are there any major new technologies in stainless steelmaking opening up new types of ore for exploitation, as the argon-oxygen decarburization process did for South African chrome ore after Rhodesian supplies were embargoed. The Canadian nickel strike and, to a lesser degree, the disruption in cobalt markets resulting from the Zairian disturbances, showed that interruptions in metal supplies could have financial effects much greater than might have been expected, on the basis of the dollar value of imports of these metals.

These four diverse historical examples illustrate two important points. First, interruptions or even complete cessation of supply from major producers of strategic materials are possible, whether as a result of international politics, internal rebellion, labor difficulties or other causes. Second, technology provided a means to respond to interruptions of supply in each of the examples. Thus, a basic question to be answered in considering the full range of possible elements in a Government policy for strategic materials is the extent to which technology can protect the U.S. economy from the adverse effects of possible interruptions in the future. The first step toward answering this question is to identify the technological alternatives to the current state of reliance on imports of strategic materials.

Technological Approaches to Reduce Materials Import Vulnerability

There are many technological approaches to reduce U.S. materials import vulnerability, and they may be combined in many different ways. For the strategic materials policymaker, it may be best to group these various approaches into a materials technology triad. The components of this triad are minerals production and metal processing, conservation, and substitution.

The production leg of the triad includes domestic production, diversified foreign production, and production of minerals from regions beyond national jurisdiction. The processing of these minerals into forms used by industry, particularly ferrochromium and ferromanganese for the steel industry, is also included in the production leg. The conservation leg includes improved manufacturing technologies that use materials more efficiently, such as improved casting methods, more efficient forging techniques, and the manufacture of parts from powdered metals. It also includes the recycling of scrap generated during the manufacture of components and of obsolete scrap retrieved from discarded products. The third leg of the triad, substitution, involves the use of materials with reduced strategic materials content in place of traditional materials. An example is the use of 9 percent chromium steel in place of stainless steel containing 18 percent chromium in certain powerplant applications. Substitution also includes the displacement of strategic materials by new materials such as advanced ceramics or composites.

Individually, no one technological approach can meet all of the varied problems that might arise with regard to the security of supply of the four first-tier strategic materials; the approaches must be combined to improve their effectiveness. Further, each provides opportunities that differ for the various materials. Thus, the most effective combination of technological approaches for dealing with materials import vulnerability varies from one material to the next.

Summary of Technological Approaches

In reviewing the outlook for technological approaches to reduce materials import vulnerbility for the four first-tier strategic materials, several points become apparent. First, there is no single solution. For example, as is shown in table 1-1, substitution is extremely important to reducing chromium vulnerability, but has little contribution to make in the case of manganese. Recycling, which is important for

Table 1-1.—Summary of Most Promising Technological Approaches to the Reduction of Strategic Materials import Vulnerability

Approach	Potential benefits[a]	Barriers to implementation
Chromium:		
Substitution	Direct substitution could now reduce U.S. chromium needs by one-third. Another one-third reduction may possibly be achieved through a 10-year R&D program.	Low cost of chromium alloys deters use of substitutes; lack of information on substitutes slows their use in times of shortage; need for further tests and experience limits near-term potential for substitution to one-third of consumption.
	Advanced materials may displace chromium alloys in certain aerospace and industrial applications.	Basic and applied research is needed to improve properties and reliability of advanced materials. Designers and engineers need better understanding of properties and limitations of advanced materials. Tests and standards need to be developed for these materials.
Conservation	Expanded recycling of scrap and waste could provide at least 20,000 tons of chromium beyond current recycling levels.	Barriers to chromium recycling are economic, not technical.
Production	Development of alternative foreign sources could provide about 30,000 to 60,000 tons, about 10 to 20% of current U.S. demand.	At current prices for chromium, there is no economic incentive to diversify suppliers. Government assistance would be required to make development of alternative suppliers more attractive.
Cobalt:		
Conservation	Recycling could recover much of the cobalt in scrap and waste that is currently lost or downgraded.	Principal barrier is economic; however, extensive recovery of superalloy scrap may require use of technology that is now limited to laboratory testing.
	Process improvements now being adopted may make significant reductions in the amount of cobalt used to make jet engine components.	Economic factors favor the adoption of process improvements.
Substitution	Direct substitutes under development could reduce the need for cobalt by 50% or more in some critical superalloy applications.	Industry has little or no incentive to expend the time and money needed to qualify alternative alloys except when there are significant performance advantages.
	Advanced materials may displace cobalt in some aerospace and industrial applications.	Barriers to adoption of advanced materials to reduce cobalt consumption are the same as for chromium, as described above.
Production	Domestic production from three sites could produce up to 8 million pounds of cobalt per year.	Current prices for cobalt and/or co-product metals are too low to justify investment without Federal subsidies.
	New foreign production could provide almost 15 million pounds of cobalt per year.	Investments are being postponed until cobalt prices rise. Lead times of 2 to 5 years are needed to bring deposits into production.
Manganese:		
Conservation	Process improvements could reduce needs for imported manganese in steel by 45% by year 2000.	Adoption of improvements will depend on incremental upgrading of domestic steelmaking facilities.
Production	Alternative suppliers to South Africa and the Soviet Union could increase production after 2 to 3 years to expand facilities.	Assured market for increased production is needed to justify investment in production and transportation facilities: U.S. would be in competition with other consumers for new production; facilities for processing ore into ferromanganese must also be available.
Platinum group metals (PGMs):		
Conservation	Recycling of catalytic converters could recover 500,000 troy ounces of PGM annually by 1995.	No significant barriers; several years will be needed to develop collection and processing infrastructure.
Production	Development of the Stillwater deposit could produce 175,000 troy ounces of PGM in the near term; additional development is possible.	Domestic production will require slightly higher prices for platinum and palladium and evidence of increased demand.

[a] The benefits accruing from the various approaches are not cumulative. For example, as scrap generation in manufacturing is reduced through improved processing techniques, the potential benefits of recycling are also reduced.

SOURCE: Office of Technology Assessment.

platinum and cobalt, is also a minor contributor for manganese. Similarly, processing efficiency, diversity of supply, and domestic production all vary in importance for each of the strategic materials.

Second, none of the approaches offers a "quick fix" to import vulnerability problems. All require a continuing commitment, whether the approach is to maintain substitution information on a current basis, or to move new materials from the laboratory to industrial use, or to encourage investment in new mines or processing facilities.

Third, the existence of technological alternatives is based on a history of long and continued support by Government, academia, and industry for basic research in materials science and engineering. Had this commitment been significantly less, fewer alternatives would be available today.

Fourth, in only a few instances is it likely that the technological approaches which offer promise to reduce import vulnerability will be implemented under normal economic and market conditions. Improvements in steelmaking technology and recycling of catalytic converters are underway and are likely to continue, as are improvements in superalloy fabrication technology. Development of the Stillwater, MT, PGM deposit is a strong possibility, although the actual decision to go ahead will rest on a positive assessment of future markets for platinum group metals. Development of advanced materials that contain no strategic materials is likely, but it is not clear how useful these materials will be in applications that now require strategic materials. For the rest of the technical approaches, the outlook for implementation is poor unless new incentives are forthcoming, provided either by the market (in the form of tightened supplies and higher prices) or by the Government (as investment assistance or price supports).

Chromium

PRODUCTION

World production of chromite, the ore from which chromium is obtained, is largely accounted for by southern African and Communist countries. In 1982, South Africa accounted for 22 percent of chromite production, the U.S.S.R. accounted for 24 percent, Albania for 12 percent and Zimbabwe for 4 percent. Another 22 percent was spread among Brazil, Finland, India, Madagascar, the Philippines, and Turkey. The processers of ferrochromium, the form used in making alloy and stainless steel, are more diversified. In the 1980-82 period, the Soviet Union and South Africa each accounted for 20 to 25 percent of world production. Japan was a midlevel producer, accounting for about 15 percent and the United States accounted for about 7 percent. These figures are static, however, and do not reflect the trend toward decreased diversity of ferrochromium production. From 1974 to 1980, U.S. ferrochromium production declined by 29 percent, Japan by 21 percent, and France by 30 percent. During the same period, South African ferrochromium production rose by 193 percent and the Soviet Union 279 percent.

Domestic Production.—Domestic resources offer few opportunities for reducing import dependence for chromium. United States chromium resources are limited to low-grade deposits, such as the Stillwater Complex in Montana, the small, discrete deposits of chromite in northern California and Oregon, and extremely low-grade chromite associated with nickel laterites such as the Gasquet Mountain deposit in northern California. The Stillwater deposit was mined under Government contract during World War II, but it is not under consideration for development now. Somewhat lower in cost to mine than the Stillwater ores, the disseminated, or podiform, chromite deposits of California and Oregon also provide a resource that could be tapped in times of national emergency, but one that is not competitive with worldwide chromite deposits now in operation.

Only one domestic chromite resource, the Gasquet Mountain nickel laterite deposit, is under consideration for development at this time. The development proposals call for this deposit to produce nickel and cobalt, with a chromite concentrate as a byproduct. Considering current prices for nickel and cobalt, the outlook for this mine is dim. Even if it does enter into operation, the production of chromite would be less than 3 percent of U.S. annual consumption of chromium.

Although only low-grade deposits of chromium have been discovered in the United States, the possibility remains that better deposits exist. High-grade chromite deposits, where they exist, are normally associated with the precambrian rock such as that which underlies much of North America. Unfortunately, only small areas of this rock are exposed. Conventional mineral reconnaissance techniques, which rely heavily on the identification of surface features associated with the desired mineral deposits, are limited to these exposed areas. In other areas, the precambrian rock is covered by thick layers of sediment or glacial debris, precluding the use of surface features to disclose the nature of subsurface deposits. Advances in exploration technology, however, may improve the outlook for the discovery of more deposits. Improved geophysical techniques, such as arial gravimetric and magnetic analyses targeted specifically at chromium, could reduce the dependence of explorationists on surface geology. Improved geochemical and core drilling technology could encourage the exploration for chromium (and other minerals) by reducing exploration costs. In the long term, improved scientific understanding of the processes that form deposits could assist explorers to identify regions in which to concentrate their efforts.

Diversified Foreign Production.—Unless major new deposits of chromite are discovered, the opportunities to diversify supplies of chromium are limited to minor expansion of small producers, such as Albania, Turkey, and the Philippines, and the exploitation of known, but undeveloped, chromite resources in the laterites and beach sands of New Caledonia and the Philippines.

The deposits in Albania, Turkey, and the Philippines are small and discrete, and it is likely that many deposits remain undiscovered. Production from these countries might be increased if techniques for identifying scattered deposits of chromite can be improved.

Technologies have been developed for the production of chromite from nickel laterites and beach sands, but the ore grades of such deposits generally range from 2 to 5 percent chromic oxide. With the major producers supplying ore that contains 35 to 48 percent chromic oxide, the lateritic and sand deposits would require substantial concentration to produce a marketable product, and the estimated cost of producing such a product is two to three times the current market price.

Ferrochromium Processing Capacity.—Before 1970, the United States had sufficient capacity to meet its needs for ferrochromium, the form of chromium used in the production of steel. Since that time, however, imports of ferrochromium have reduced the domestic industry's share of United States demand and, with time, the capacity to produce ferrochromium domestically is also decreasing as furnaces and plants are decommissioned. As domestic processing capacity declines, the United States loses its flexibility to turn to alternative sources of ore from countries that do not have their own ferrochromium facilities.

The decline of the domestic industry is directly related to the cost of operation. Costs of power, labor, and transportation are, in general, lower for the producers in countries where chromium ore is mined than for U.S. firms. In addition, national policies in the producer countries often provide economic incentives for local processing of ferroalloys.

The advantages enjoyed by producing countries are not insurmountable. The growing need to blend together ores that have different chemical and physical properties means that all producers will need to import ores, so that all producers will pay the additional cost of transporting ore rather than the more concentrated ferroalloy. Labor rates in many producer countries are now quite low, but are likely to increase more rapidly than in the United States, thereby narrowing the cost differences. Improvements in the technology for measurement and automatic control of processing operations should provide gradual improvements in domestic plants. In the longer term, advanced furnaces may provide means to reduce energy consumption, further reducing advantages held by some foreign producers. Economic and trade agreements may also help narrow the economic gap. With the advantage of proximity to consumers, which gives U.S. producers an advantage in responding to special orders placed by the steel industry, technical improvements in ferroalloy facilities could improve the potential to maintain a domestic ferrochromium industry capable of processing ore from a variety of foreign sources.

In the long term, with wise adoption and application of technology, the industry may be able to keep a significant share of the domestic market for ferrochromium, ferromanganese, and other ferroalloys. In the near term, however, there is little technology can do; so, during this period, the domestic industry is likely to need economic and political assistance if it is to preserve a market presence against foreign competition.

CONSERVATION

Chromium-bearing manufacturing and obsolete scrap are marketable products that account for about 10 to 15 percent of U.S. consumption of chromium. Because recycling of manufacturing scrap is already at a high level, there is little opportunity to increase chromium recovery in this area. There are, however, significant opportunities to increase the recovery of chromium from obsolete stainless steel scrap and from waste produced by steelmaking and chemical processing plants.

Recycling of obsolete stainless steel scrap is difficult because of the long lifetime of stainless steel products, the wide dispersion of the products through the economy, and the difficulty of separating the stainless steel from other materials in discarded products. The most promising prospect is in the automotive area. About one-third of all obsolete stainless steel scrap is obtained from junked automobiles; even so, only 30 to 40 percent of the chromium contained in the cars is recovered. The best opportunity for increasing chromium recovery from automobiles lies in the catalytic converter. The shell of the converter, which is made from Type 409 stainless steel, contains 1.8 to 2.6 pounds of chromium—over half of the total chromium content of the automobile. Since this type of stainless steel is magnetic, it is not easily separated from other magnetic parts either before or after the cars are shredded. However, interest in recycling of the platinum in the converters is increasing (see "Platinum Group Metals" below) and the converters are starting to be removed for separate processing, which makes the stainless steel shell available for recycling. If recycled separately, the converter shells could produce about 5,000 to 7,000 tons of chromium per year, or up to 3 percent of the 1981 U.S. demand for chromium in stainless and alloy steels.

Opportunities for recovery of chromium from industrial wastes are difficult to quantify because of a lack of up-to-date information. In 1974, the most recent year in which data were compiled, chromium lost in industrial waste was estimated to be over 28,000 tons, including over 17,000 tons from various metallurgical processes. Since that time, several firms have instituted both internal and commercial waste processing programs. For example, Inmetco, a subsidiary of Inco, processes flue dust, mill scale, and grinding swarf containing 3,100 tons of chromium with chromium recovery rates of about 90 percent. Other facilities have been developed to process other forms of scrap and waste.

Chemical and metal finishing industry wastes were estimated to contain over 3,000 tons of chromium in 1974, which was then almost entirely lost. Although recycling or regenerating the chromium from these wastes is expensive, the cost of meeting strict standards for the disposal of waste in landfills could encourage the recovery of metals. Furthermore, the value of the metal could help lower the costs of processing the waste for disposal. Several recovery technologies, including closed-loop systems to extend the life of acid baths, have been under development and hold promise to reduce chromium losses in the future.

SUBSTITUTION

Direct Substitutes.—The most important use of chromium is in metallurgical applications, where it provides properties of hardness, wear resistance, high-temperature strength, and resistance to oxidation and corrosion. It is in these uses that substitution offers the greatest opportunities to reduce the requirements for imported chromium.

Because of its relatively low cost, availability, history of satisfactory performance, and familiarity to designers, chromium-containing steels, particularly stainless steels, are widely used, even in applications that do not require the superior performance provided by the high chromium content. There are many opportunities to use materials with reduced chromium or no chromium at all, but there is no single substitute material that can serve in all of the applications where stainless steel is now used. Appropriate substitute materials must be selected for specific applications. Some of the more promising substitutes for stainless steel are summarized in table 1-2.

It is important to note that there are few incentives to replace stainless steel in most applications. As a result, most potential substitute materials remain at the laboratory stage because, without economic incentives to adopt alternative materials, private industry will not spend the money required to move the materials to commerical use.

Advanced Materials.—In the long term, nonmetallic and unconventional metallic materials may provide alternatives to chromium-bearing stainless and alloy steels and superalloys. Ceramics are being developed for possible use in engine components, power plants, and bearings—all applications that now use stainless or alloy steel—and in gas turbine engines in place of superalloys. Advanced composites may be used in applications that require high strength and light weight. New metallic materials, including rapidly solidified metals and long-range ordered intermetallics may provide alternative materials for use at high-temperature applications, such as turbine components in jet engines, that otherwise require alloys with chromium contents of 20 percent or more.

However, advanced materials must overcome substantial barriers before they can significantly reduce the need for chromium or other strategic materials. With few exceptions, these materials are still in early stages of development. Considerably more work must be done in the laboratory to improve the properties of the materials, and processing and manufacturing methods must be developed to accommodate their special properties. Even then, the materials must gain acceptance by designers, who will evaluate them not only on eco-

Table 1-2.—Substitution for Chromium in Metallurgical Applications

Application material	Current material	Alternative	Developer	Status
Boiler tubes in conventional and nuclear powerplants	Type 304 stainless steel (18% chromium)	Modified 9% chromium/1% molybdenum steel	Oak Ridge National Laboratory	In process of certification by ASME code committees
General use in moderately corrosive or oxidizing environments	Type 304 stainless steel	Manganese-aluminum steels	Diverse locations in U.S. and other countries	Laboratory stage in U.S. Minor practical applications in China
High-temperature oxidizing environments	Type 304 stainless steel	8% aluminum/6% molybdenum steel	Bureau of Mines	Laboratory stage
Corrosive environments (chemical processing)	Type 304 stainless steel	9% chromium alloy steel	Bureau of Mines/ Inco	Laboratory stage
General use (moderate corrosion and oxidation uses)	Type 304 stainless steel	12% chromium stainless steel	NASA Lewis Research Center	Laboratory stage
Automotive exhaust systems and catalytic converters	Type 409 stainless steel (12% chromium)	6-12% chromium alloy steel	ARMCO	Laboratory stage

SOURCE: Office of Technology Assessment.

nomic grounds but on the familiarity that grows with practical experience.

Cobalt

PRODUCTION

Cobalt is generally produced as a byproduct of nickel or copper mining, its sales supplementing the revenues from these other products. Only rarely is it mined for its own sake. The largest cobalt producers, Zaire and Zambia, produce cobalt from their copper mines. Canada and Botswana produce it from nickel-copper mines, and Cuba and the Philippines recover it from nickel laterites. Less commonly, cobalt may also be found in deposits of lead, iron, and manganese. Only in Morocco has cobalt been produced as a principal product. As a result of the wide distribution of cobalt-bearing ores, diversified production, both domestic and foreign, is a more promising option for the reduction of import vulnerability for cobalt than for chromium, manganese, or platinum group metals.

Domestic.—In the aftermath of the Korean war, the United States obtained cobalt from domestic sources, largely by granting Federal subsidies to the mine operators. Three deposits, the Blackbird mine in Idaho (a copper-cobalt mine), the Madison mine in Missouri (lead-cobalt) and the now-depleted Cornwall mine in Pennsylvania (an iron deposit with small amounts of cobalt), provided the bulk of domestic cobalt. In addition to these proven deposits, several other deposits are known and have been studied as possible domestic sources. These are the copper-nickel deposits of the Duluth Gabbro in Minnesota and the cobalt-containing nickel laterites in northern California.

At current and projected prices for cobalt and other metals that can be produced from the Blackbird mine, the Madison mine, the Duluth Gabbro, and the nickel laterite deposit at Gasquet Mountain in California, domestic cobalt production is economically unattractive. Unless prices for cobalt, nickel, lead, and copper show major and prolonged increases, private industry will not develop any of these deposits. Increases on the order of 50 percent for nickel and copper, or 100 percent or more for cobalt would be necessary to encourage private investment. At these higher prices, domestic production of cobalt could be significant. Development plans for the Blackbird mine call for the production of 3.7 million pounds of cobalt per year, for the Madison mine 2 million pounds, and for the Gasquet Mountain deposit 2 million pounds. The lives of these mines vary from 10 to 20 years, based on proven reserves. Potential cobalt production of hypothetical mines in the Duluth Gabbro is estimated to be from 1 million to 2 million pounds annually.

Diversified Foreign Production.—The high market prices that are required for domestic production of cobalt have led developers to look for deposits in foreign countries that offer more attractive economics. With long-term price increases less extensive than those required to make U.S. deposits economic, cobalt production from nickel mines in Canada and Australia, which accounted for 10 percent of world production in 1980, can be increased substantially.

Increases in cobalt and nickel prices would also improve the prospects for the development of cobalt deposits in Indonesia, New Guinea, New Caledonia, and Peru. These four deposits are summarized in table 1-3. The total potential cobalt production of these four deposits could be 14.7 million pounds per year if they were all to enter production. As with the domestic deposits of cobalt, however, these four are unlikely to be developed under current economic conditions. In fact, development at Gag Island was recently halted due to poor economic outlook and partnership disagreements,

Table 1-3.—Potential New Foreign Cobalt Production

Site	Estimated production (million pounds/year)	Leadtime to start production
Gag Island, Indonesia	2.8	2 to 3 years
Ramu River, New Guinea	5.9	5+ years
Goro, New Caledonia	2.0	3.5 to 5 years
Marcona Mine, Peru	4.0	2 years
Total	14.7	

SOURCE: Office of Technology Assessment

and development of the other three deposits awaits improved markets for nickel and cobalt.

Ocean Resources.—For over 100 years it has been known that in the depths of the ocean there are deposits of nodules and crusts of manganese that contain copper, nickel, and cobalt, sometimes in concentrations that would be very attractive in land-based deposits. Advances in the technology for ocean resource exploration and development during the 1960s and 1970s raised the possibility of recovering these minerals from the seabed. Commercial interest centered on the manganese nodules of the east central Pacific ocean where the nickel, copper, and cobalt contents were at their highest. After a peak of interest in the late 1970s, however, interest in the development of these resources declined sharply. Although uncertainties about the legal right to mine the resources contributed to the decline in interest, more significant were the increases in the projected cost of exploitation (based on the analysis of data from prototype tests conducted in 1979 and 1980) and the realization that assumptions of future increases in the price of nickel and copper were overly optimistic. The high cost of building and operating an ocean mining system is compounded by the legal uncertainties arising from U.S. abstinence from the seabed mining provisions of the Law of the Sea Convention, and by the cost of development and testing remaining to be done on mining systems. With time, as higher grade land-based resources are depleted, the resources of the deep sea floor may well become a major source of cobalt and other metals. At this time, however, land-based sources of cobalt, whether foreign or domestic, appear more attractive for commerical development.

CONSERVATION

There are a number of conservation alternatives to reduce U.S. requirements for cobalt. The manufacture of superalloy components is a particularly attractive area for improvement. A considerable amount of machining is performed on jet engine components, resulting in large quantities of manufacturing scrap. Ratios as high as 10 to 1 for purchased metal to metal used in the engine are seen, with ratios of 6 to 1 being common. Less than 50 percent of this superalloy manufacturing scrap is recycled for use in superalloys; the rest is used in steel for its nickel and chromium content, is exported to foreign consumers, or is disposed of as waste. Obsolete parts made of superalloys are contaminated with carbon and sulfur, and generally are not recycled for production of jet engine components. Past failure to utilize scrap has been based, in part, on engine manufacturers' standards that limited the use of scrap and, in some cases, prohibited its use altogether, due to concern that contaminants would not be removed in refining processes and the resulting alloy would be unsuitable for use in critical applications. With experience, it has been possible for manufacturers to relax the specifications to allow the use of superalloys that contain up to 50 percent recycled materials (principally from manufacturing scrap) in aircraft applications.

Recent advances in remelting and refining technology have led to the development of processes that could refine manufacturing scrap, and even some obsolete scrap, to produce new alloys that can meet the strictest of standards required by aircraft engine manufacturers. Processes have also been developed to recover individual elements from mixed alloy scrap. The usefulness of these processes is limited, however, because they have only been tested in the laboratory or in small pilot plants. Further time and effort are needed to determine their technical and commercial feasibility as full-scale facilities.

A second conservation measure that could reduce import vulnerability for cobalt is the use of more efficient manufacturing technologies. Particularly important among these, for superalloys, are near-net-shape technologies. These include powder metallurgy, in which powdered metals are pressed under high pressure and temperature into a form close to the final shape of the desired component; hot isothermal forging, in which materials are deformed under extremely plastic or superplastic conditions to near final shape; and advanced precision casting methods that allow the production of complex shapes as a single part, eliminating many machining steps that would otherwise produce scrap, much of which would be downgraded or lost.

An example of the benefits of these advanced manufacturing processes is the production of the turbine disk for the Pratt & Whitney F-100 jet engine. When first designed, this 15-pound part was forged from a 250-pound billet of Astroloy (17 percent cobalt), which resulted in 235 pounds of chips containing 40 pounds of cobalt. With isothermal forging, the billet weight is reduced to 126 pounds and the material used is IN-100 (18.5 percent cobalt) instead of Astroloy; the result is 110 pounds of chips containing 20.5 pounds of cobalt—almost a 50 percent saving in cobalt. Future improvements are expected to reduce chip formation to 35 pounds of material containing less than 7 percent cobalt; the result will be a net cobalt savings of over 80 percent, compared with the original manufacturing process.

Improvements both in recycling and in manufacturing efficiency act to reduce U.S. dependence on imports. However, the economic factors that may impel manufacturers to adopt them are different. Manufacturing improvements are likely to continue because the improvements result in overall cost savings and performance benefits, not because they reduce cobalt consumption, per se. Advances in recycling technology are much more dependent on a specific interest in conserving cobalt; they are likely to occur slowly, if at all, unless price increases or supply uncertainties provide incentives for further development in the reuse of superalloy scrap for critical applications.

SUBSTITUTION

Owing largely to the uncertainty of cobalt supplies following the 1978-79 disturbances in Zaire, the U.S. Government sponsored research into the potential to reduce strategic material requirements in jet aircraft. Results of laboratory tests indicate that cobalt content of some superalloys currently used in aircraft engines could be reduced by 50 percent or more through the use of new alloys. Some steps along this line were taken by jet engine manufacturers through the substitution of nickel-based superalloys containing little or no cobalt for cobalt-based superalloys and cobalt nickel-based superalloys with high cobalt content. Further steps along these lines are more difficult, however. The certification of a new alloy for use in critical aircraft applications is an expensive and time-consuming process, one that companies will not carry out unless the substitute provides clear performance benefits or unless faced with high metals prices or extreme and prolonged uncertainty about the availability of cobalt.

As with chromium, long-term opportunities to develop substitutes for cobalt-bearing alloys are enhanced by the development of advanced materials. Ceramic cutting tools are already being used in place of high-temperature tool steels or cemented carbide tool bits that contain cobalt. Ceramics and carbon-carbon composites have shown some potential for high-temperature applications that now require superalloys. Advanced metallic materials, including rapidly solidified materials and long-range ordered alloys, also have high-temperature characteristics that may lead to their future application in place of conventional cobalt and chromium-bearing superalloys.

Manganese

About half of the manganese consumed in the production of steel is contained in iron ore and scrap. Since these materials are available domestically or from Canada, this supply of manganese is relatively secure from interruption. The remainder of the manganese in steel is provided in the form of manganese ore and ferromanganese that the United States must import.

PRODUCTION

World manganese production is dominated by a limited number of very large deposits that, because of their large reserves and high manganese content, are very economical to operate. The major producers, South Africa, the U.S.S.R., Gabon, Australia, China, and Brazil, accounted for all but 5 percent of world production in 1982. In addition, Mexican production accounted for 2 percent of total world production. Production is concentrated in the U.S.S.R. (41 percent of 1982 production) and South Africa (23 percent).

Domestic Production.—The United States is endowed with only relatively small and low-grade deposits of manganese. Although these deposits were exploited during World War II, they are not economically competitive with the world class deposits now in production. Prices between $8 and $35 per long ton unit (equivalent to 22.4 pounds of manganese) are estimated to be required for domestic deposits to become economic. With the current market price ranging between $1.45 and $1.75 per long ton unit, it is doubtful that domestic manganese will be developed, although some production of low-grade ferruginous manganese ores (defined as ores containing less than 35 percent manganese) is possible.

Undiscovered deposits of manganese of commercial or near-commercial grade may exist in the United States. However, manganese cannot be detected by airborne methods, so exploration must be conducted on the ground, raising the cost of initial reconnaissance. Wide distribution of manganese in rock and soil makes it difficult to distinguish traces of manganese associated with ore deposits from the general background concentration, reducing the usefulness of geochemical exploration methods. If exploration for manganese is to be encouraged, improved theories of formation must be developed so that promising locations for deposits can be identified and geochemical and geophysical methods can be concentrated in these more promising areas. Given the availability of manganese at low cost from a variety of suppliers, it is unlikely that private firms will conduct research aimed at locating domestic manganese deposits since the benefits, if any, would occur far in the future.

Diversified Foreign Production.—Increased production of manganese at the Groote Eylant mine in Australia offers the best opportunity for diversification away from South Africa. High-grade ore and proximity to ocean transport make expansion of this deposit relatively easy. Mexico also could expand its production, but Mexican ore is lower in quality than that of the major producers. Expansion of this deposit would be more costly than expansion of the Australian deposit because, in addition to the cost of expanding mine capacity, additional investment to increase the capacity of the ore upgrading equipment would be necessary. Possibilities for diversification are also limited in Gabon, where a long transportation line that includes an aerial tramway limits the potential to increase the production rate. In Brazil and China, a large share of manganese production is dedicated to the current and future needs of their domestic steel industries. Although expansion of manganese production for export is possible in these countries, it is not currently planned.

Ocean Production.—Certain areas of the ocean are favorable to the formation of crusts or nodules containing up to 30 percent manganese. Manganese contained in these deposits is finely disseminated through the material and not easily processed into a conventional manganese ore. With further development of ocean mining technology, the nodules located on the Blake Plateau off the coast of Florida could become a new domestic source of manganese but costs of production would be similar to those of other domestic ores and much higher than many foreign ores. Similarly, manganese could be recovered as a byproduct of deep ocean mining in the Pacific for nodules rich in nickel, copper, and cobalt. However, mining of the Pacific nodules appears to be far in the future.

Manganese Processing Capacity.—For its largest and most important application—as a processing and alloying agent in the manufacture of steel—manganese ore must be processed into ferromanganese. As is the case with chromium, the United States has become dependent on foreign processing of manganese ore to meet much of its demand for ferromanganese. Since the equipment and processes for ferromanganese production are similar to those for ferrochromium (in fact, the facilities are sometimes converted from one product to the other, although at a reduction in efficiency), the technical approaches to maintain a domestic processing capacity are also similar. Technological advances offer little help to the domestic industry in the immediate future. However, improved technology for monitoring and controlling ferromanganese furnaces could raise the productivity of domestic facilities to a limited degree. Over a longer period, the development, refinement, and adoption of new high-voltage and plasma arc furnaces may give domestic producers an edge in efficiency over foreign producers who do not adopt the technology and allow them to be competitive with those who do.

CONSERVATION

Improvements in steel production technology provide the best prospect for the reduction of manganese import vulnerability. Careful measurement of sulfur levels and manganese additions, resulting in manganese contents near the lower level allowed by steel specifications, can result in reductions of manganese consumption per ton of steel by about 8 percent. External desulfurization, which reduces manganese requirements, may provide even more dramatic savings and so may up-to-date steelmaking techniques such as continuous casting, which keep to a minimum internal, or "home" scrap that in each cycle through the steelmaking process contributes to inevitable losses of manganese in slag.

As shown in table 1-4, 35.6 pounds of manganese are used on average to produce one ton of steel, 17.8 pounds of which is provided by imported manganese ore and ferromanganese. Only 13.8 pounds remain in the steel while the other 21.8 pounds is lost in slag, dust, and waste. By the year 2000, the average manganese content of steel is likely to decline slightly to 12.2 pounds per ton of product, but major reductions are expected in the amount of manganese lost. The net result will be a reduction in total manganese consumption per ton steel from 35.6 to 24.8 pounds. Even more striking, and more important from a security of supply viewpoint, the consumption of imported manganese ore and ferromanganese is estimated to decline from 17.8 pounds per ton of steel to 9.5 pounds per ton, a decline of over 45 percent from current levels.

Table 1-4.—Current and Projected Manganese Consumption in U.S. Steel Production (pounds of manganese per ton of steel product)

	Current	Projected—2000		
	(1981-82)	Expected	Best	Worst
Inputs:				
Manganese products:				
Manganese ore	1.9	1.2	1.0	1.5
Ferromanganese	15.9	8.3	5.5	12.2
Total	17.8	9.5	6.5	13.7
Iron and steel products:				
Iron ore and sinter	12.9	8.5	7.1	10.1
Purchased ferrous scrap	5.0	6.8	6.9	6.6
Total	17.9	15.3	14.0	16.7
Outputs:				
Retained in steel products	13.8	12.2	11.2	13.4
Losses (slag, dust, waste)	21.8	12.6	9.4	17.0
Total manganese use	35.6	24.8	20.6	30.4

SOURCE: Office of Technology Assessment.

SUBSTITUTION

The bulk of manganese consumption is in steelmaking, and in this application there is no satisfactory alternative, with the exception of the use of rare earths in a limited group of applications that can justify the sharply higher cost.

Platinum Group Metals

PRODUCTION

The Soviet Union and South Africa account for over 90 percent of world PGM production, with most of the remainder coming from Canada. Production in all other countries accounts for only 1 percent of world production. Canadian production results from byproduct recovery from copper-nickel ores and cannot be expanded substantially without corresponding increases in the production of these metals. Since economics do not favor increases in copper or nickel production, Canada cannot be considered an important diversification opportunity.

The United States offers the only significant opportunity to affect, even slightly, the dominating role of South Africa and the U.S.S.R. in PGM production. While minor amounts of PGM are obtained as a byproduct from three U.S. copper mines and, in the past, from placer deposits such as Goodnews Bay, AK, there are plans under consideration to develop resources of platinum group metals in the Stillwater Complex in Montana. This deposit could produce 175,000 troy ounces of platinum group metals annually, or between 2 and 3 percent of current world production. This operation is under evaluation and review, and the decision to go ahead with development will rest on assumptions of stable or increasing metal prices.

Undiscovered domestic deposits of platinum group metals are almost certain to exist, most likely as placer deposits such as Goodnews Bay and as byproducts of copper-nickel sulfides. Although less likely, another major domestic PGM deposit, similar to the Stillwater Complex, could exist. Exploration for such a deposit would face problems similar to those described for chromium and for cobalt-bearing copper-nickel sulfides. As with those metals, prospects for success in exploration for PGMs would be enhanced by improvements in geophysical, geochemical, and drilling technology and by advances in the understanding of the geologic processes that formed PGM deposits.

CONSERVATION

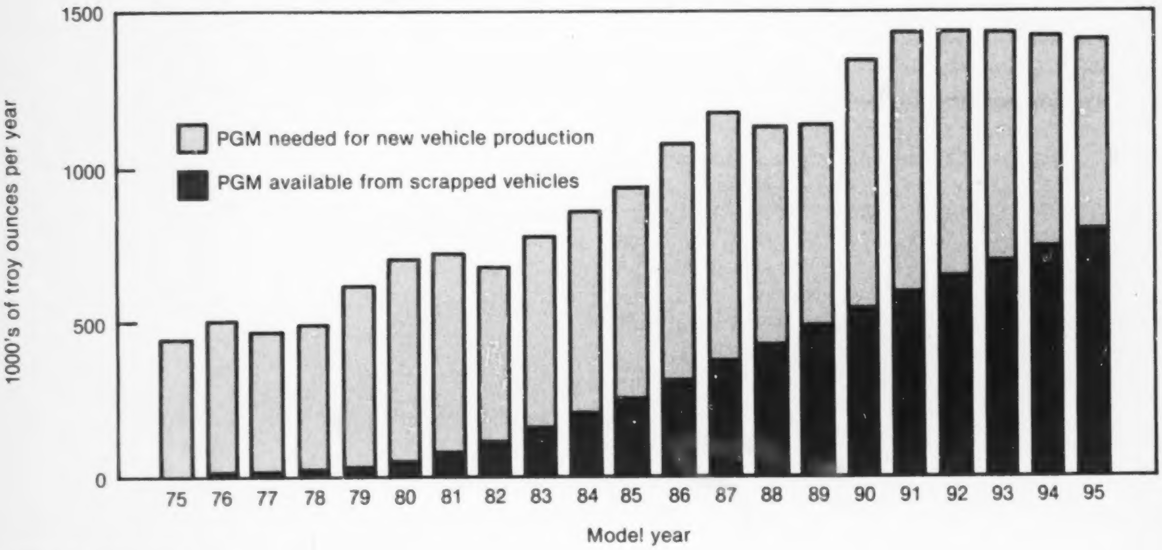
As with manganese, conservation technology provides the greatest opportunity for the reduction of materials import vulnerability in platinum group metals. Platinum contained in industrial catalysts is already extensively recycled, but the recovery of platinum group metals from electronic scrap and from obsolete automotive catalytic converters is less extensive. There are no major technological barriers to recovery of platinum group metals from either type of scrap. Instead, the principal barriers are in the collection of scrap from widely dispersed locations for processing at central facilities. Scrap from electronic manufacturing plants is the easiest to collect, and recycling operations are well underway in this area. Obsolete electronic components are also processed, but this is hampered by the high labor intensity required to identify and separate platinum-bearing components. Catalytic converters are now beginning to enter the scrap yards in sufficient quantities to interest platinum recyclers, and a number of firms are showing interest in processing the converters to recover the contained platinum group metals. Platinum metal available annually from catalytic converters, which was about 115,000 troy ounces in 1982, is projected to grow to over 800,000 ounces in 1995 (fig. 1-2). Actual recovery will probably not exceed 500,000 troy ounces, since only about 70 percent of obsolete cars and trucks reach automotive dismantlers where converters may be removed for recycling, and some PGM is lost in processing.

It is also possible that new engine designs may allow the reduction of pollutants without the need for catalytic converters. However, the wide-scale adoption of any significantly new automotive engine is not likely until the next decade, and long-term prospects will depend on price and performance factors, not on potential savings of platinum group metals.

SUBSTITUTION

Substitution opportunities for platinum group metals are greatest for electronic components. Gold is a substitute for platinum in electric and communications relays, with substitution decisions being based on the relative prices of gold and platinum. Silver and palladium alloys may be used in place of pure platinum in many applications, although platinum may offer superior performance and reliability. Palladium, now used in ceramic capacitors in rapidly increasing amounts, may be subject to substitution in 5 to 10 years as technologies using silver, nickel, and lead electrodes are improved. In catalytic applications, however, the outlook for substitution is dim. Unless new developments arising from advances in the study of surface science and chemistry lead to new catalytic systems, the high efficiency and long lifetime of platinum catalysts make them virtually irreplaceable.

Figure 1-2.—PGM Demand vs. Potential Supply From Recycling



SOURCE: Sierra Research.

Implementation of Technological Approaches

There are many technological approaches to reducing import vulnerability for each of the four first-tier strategic materials. These are summarized in the preceding section. They vary in the potential contribution they could make to the reduction of vulnerability, in the cost of carrying them out, in the period of time when they are effective, and in the assurance that they will fulfill their potential. These factors, as well as the interrelationships among the approaches, mean that it is important to direct and coordinate the implementation of technology toward specific goals. As a result, the management of strategic materials policy is critical to the successful implementation of the various approaches. The following sections address alternatives available to the United States, both in the general management of materials policy, and in the implementation of the technologies.

Legislative Guidance for Strategic Materials Policy

The 1980 National Materials and Minerals Policy, Research and Development Act (Public Law 96-479) provides a basic policy framework that could be used to develop and evaluate various technological approaches for reducing U.S. import vulnerability. The law emphasizes the importance of research and development activities related to all stages of the materials cycle (from exploration and mineral extraction through recycling and disposal) in addressing materials problems. The law applies to all materials, not just those for which the United States is import dependent, but many of its provisions apply to strategic materials in particular.

The Critical Materials Act (Public Law 98-373) requires the Administration to establish a Critical Materials Council, reporting to the Executive Office of the President. The Council is required, among other things, to prepare a critical materials report and assessment, to be reviewed and updated on a biennial basis, and also to prepare a Federal program plan for advanced materials, to be annually reviewed. The Council is also to review annual authorization and budget requests related to Federal material activities, so as to ensure close coordination of goals and directions of such programs with Council policies.

In addition, several other laws, already in place, could be employed should Congress wish to encourage private industry to adopt technical alternatives to reduce import vulnerability. Title III of the Defense Production Act (DPA) of 1950 authorizes direct Federal subsidies, purchase commitments, loan guarantees, and other instruments to assure availability of essential defense materials and industrial processing capabilities. The main use of Title III has been to encourage domestic production of strategic materials, especially during the Korean war and its aftermath, but DPA also could be used to encourage other private sector actions, such as development of processing technologies and substitute materials. Congress, in April 1984, authorized the appropriation of up to $100 million to the Department of Defense for Title III projects for fiscal years 1985 and 1986, and provided new criteria for Presidential review of proposed projects before they are undertaken. Other measures of potential relevance to implementation of these technical alternatives include Federal stockpiling law (comprehensively amended in 1979 as the Strategic and Critical Materials Stock Piling Revision Act), the Minerals Policy Act of 1970, and the Stevenson-Wydler Technology Innovation Act of 1980, which emphasized transfer of federally developed technological innovations to the private sector.

Structure and Information for Strategic Materials Policy

The 1980 materials act required the Executive Office of the President to assume a more active role in coordinating and formulating materials policy, beginning with preparation of a materials program plan to be submitted to Congress by the President on a one-time basis. The plan, submitted in April 1982, emphasized domestic production and stockpile issues. It did not encompass the full range of technological issues (including substitution and recycling) emphasized in the 1980 act.

In spite of strong statements of interest in strategic materials issues, the Administration has yet to carry out all of the provisions of the 1980 act. Specific reports required of the White House Office of Science and Technology Policy (OSTP) have not been submitted to Congress, and a Department of Defense report (due to Congress in late 1981) has not yet received Administration clearance. Although a policymaking structure, based in the Cabinet Council on Natural Resources and the Environment and the renewed Committee on Materials, was established by the Administration, there is strong evidence that materials policymaking procedures remain relatively uncoordinated, both among agencies and among technological approaches.

It was the goal of the 1980 act to require the coordination of agencies over the range of materials technologies. Since this goal has not been fulfilled, Congress may wish to consider further action to assure compliance, for example by establishing specific reporting dates for the OSTP and the Department of Defense, and by requiring submission of a revised program plan, with the explicit requirement that the plan include evaluation of the role of substitution and conservation technologies in U.S. strategic materials policy.

Another alternative to improve the coordination and direction of Federal strategic materials policy would be to require the Administration to prepare, on a regular basis, a multi-year strategic materials program plan that would establish long-term goals and objectives for materials policy. Such a plan could be submitted on a 4-year schedule, reflecting the long-term goals of each Administration.

Goals, Objectives, and Coordination of Federal Materials R&D

The Federal Government is the principal sponsor of research related to strategic materials. This research is conducted through many agencies in the Government, with the Departments of Defense, Energy, Interior, and Commerce and the National Aeronautics and Space Administration being major sponsors. In the past, this research has succeeded in developing many of the technological alternatives identified in this report. However, goals of this research are often narrowly directed towards problems of specific interest to the sponsoring agency.

Many of the technological approaches identified in this report will yield their benefits only in the medium to long term. To obtain these benefits, executive branch policies need to be clearly defined and stable over a number of years. Establishment of research priorities among materials, identification of specific objectives for Federal programs, and formulation of overall strategies may be needed so that individual agencies can better plan their research, development, and budget priorities.

Information developed so far in response to the 1980 materials act is insufficient to provide a basis for coordinated interagency responses to strategic material issues. A 1983 inventory of materials research conducted by the Committee on Materials (COMAT) did not disaggregate research funds by specific material or by research activity. Nor has COMAT required individual agencies to identify all strategic materials research within their own organizations.

Without more detailed information as to the level of research support, by agency, by type of research and by material, Federal objectives for strategic materials policy cannot be established in an effective manner. In order to strengthen the Federal mechanism for policy formulation, Congress may wish to provide additional guidance to the Administration for the review of Federal strategic materials R&D as required by the Critical Materials Act.

Mineral Production and Metal Processing

The current distribution of mineral production and metal processing facilities around the world is dictated largely by the economics of exploitation; although national policies to encourage mineral development, promote employment, gather foreign exchange, or protect the environment also affect the flow of investment. The limited number of high-grade deposits of the four first-tier strategic materials has resulted in a narrow range of producers, and policies of foreign governments to promote local economic interests are contributing to a declining role for domestic firms in the ferroalloy processing industry. Although the pressures of market economics and of the development policies of producer nations are strong, actions to expand the range of suppliers, both through diversity of foreign supplies and domestic production, can be taken. Four alternatives to broaden the range of suppliers and producers are discussed below. The opportunities for production of strategic metals from known domestic deposits are summarized in table 1-5.

Domestic Production of Strategic Materials

Reasonable prospects exist for domestic production of 5 to 10 percent of U.S. demand for platinum group metals. Opportunities for the development of domestic resources of other first-tier strategic materials are limited to several low-grade cobalt deposits. Industry evaluation of these deposits, located in Idaho, Missouri, and California, indicate that about 7.7 million pounds of cobalt could be produced annually over a 10- to 15-year period. However, at current market prices for cobalt (and for the nickel, copper, lead, and zinc also found in the various deposits) development of these resources in competition with the existing low-cost producers in Zaire and Zambia will not proceed. Further R&D on ore concentration and processing systems might improve the outlook for development somewhat, but the only means to ensure the development of these resources is through Government purchase contracts for metal produced from the mines. Production of cobalt from the Idaho and Missouri deposits would require long-term (10 years or more) commitments to purchase cobalt output at $16 to $25 per pound. With recent contracts

Table 1-5.—Outlook for Development of Known Domestic Deposits of Strategic Resources

	Chromium	Cobalt	Manganese	Platinum
Good News Bay, AK	—	—	—	1-2
Stillwater Complex, MT	3	—	—	1-2
Madison Mine, MO	—	2-3	—	—
Blackbird Mine, ID	—	2-3	—	—
Gasquet Mountain, CA	2-3	2-3	—	—
Duluth Gabbro, MN	—	3	—	3
Domestic Manganese	—	—	3	—

—Not applicable.
1—Economic at current prices.
2—Marginally economic to subeconomic—under consideration for exploitation.
3—Subeconomic—not considered for commercial exploitation at current metals prices.

SOURCE: Office of Technology Assessment

for cobalt from Zaire running up to $12 per pound, the cost of subsidizing mine production of 2 million pounds of cobalt would run between $8 million to $26 million per year. For this cost, the United States would be assured of cobalt production amounting to 16 percent of 1981 domestic consumption.

According to industry estimates, development of the Gasquet Mountain deposit at current prices for nickel would require cobalt prices in the $20 to $25 per pound range. However, an increase in the price of nickel from the 1983 average of $2.20 to $3.50 per pound might make cobalt economic at about $12.50 per pound. However, such a dramatic increase in the price of nickel is unlikely.

Exploration for Domestic Resources

The fact that known domestic resources of strategic materials are very limited does not rule out the possibility that there may be significant deposits, as yet undiscovered. However, little domestic exploration for these minerals is going on. The reasons are the high cost of exploration, combined with industry pessimism about the likelihood of locating deposits of chromium, cobalt, or manganese that can be profitable in current and projected markets.

Several steps may be taken to increase the potential for discovery of domestic resources of the first-tier materials. The Government can provide economic incentives, principally through the tax system, to improve the economics of exploration. The cost of the incentives could be reduced by making them effective only for exploration that leads to the development of the target materials. However, tax incentives can only improve project economics by a marginal amount, so other action might be required if exploration for strategic materials is to be encouraged.

Targeting of Government mineral resource assessments toward the first-tier materials and increasing the detail of the assessments could identify areas of favorable potential for strategic materials. Government-supported research on improved geophysical and geochemical technologies could reduce the cost of prospecting and exploration for these materials. The lower costs, combined with improvements in techniques directed toward the desired materials, could increase private exploration for the first-tier materials.

Improved understanding of the geological processes that form deposits of strategic materials offers the greatest opportunity to expand domestic strategic materials resources. The benefits of increased research into the process of mineral formation and into techniques of predictive geology will only be seen in the long term, but, since many promising areas for the first-tier materials are covered by layers of glacial debris or sediment, predictive methods may be essential if the Nation's resource endowment is to be assessed.

Diversity of Foreign Supplies

The potential to diversify supply to reduce U.S. materials import vulnerability is greatest for cobalt and manganese. There are also opportunities to diversify somewhat the supply of chromium. Supply diversity, however, requires investment in and construction of new or expanded mining and transportation facilities. The distribution of world resources and the economic policies of producer countries have resulted in the current distribution of production, so policies meant to encourage diversity of supply must somehow change the economics of production in desired locations to attract investment.

A first step to diversity of suppliers is for the Government to identify and make known to private investors the most promising diversification opportunities. A basic program for this purpose is now underway in the International Development Cooperation Agency where the Trade and Development Program supplies funds for resource assessments of deposits of strategic materials, identifies potential U.S. participants in development activities, and brings the potential participants together with resource experts and officials in the foreign country.

In some cases, uncertain legal environments or restrictive foreign investment laws discourage development of mineral deposits. Prospects for the diversification of supply of strategic materials could be improved by coordinating actions by U.S. Government agencies, including the Department of State, the Department of Commerce, the Export-Import Bank, the Overseas Private Investment Corporation, and U.S. participation in international development banks and United Nations activities, to improve both the political and the economic climate for the development of strategic materials in specific countries. A program of this type could be an integral part of U.S. foreign affairs activities, perhaps consisting of a redirection of current resources and efforts rather than a commitment of new or increased Government funds. If desired, however, economic incentives, such as foreign assistance for infrastructure development or special tax treatment for U.S. investors, could be used to promote investment in specified projects.

In all of the approaches to diversify supplies of strategic materials, it is important that the Government target its efforts at specific materials and specific countries. In this way, the effectiveness of the Government's resources can be maximized and side effects, such as the promotion of foreign production of nonstrategic minerals in competition with domestic mines, can be avoided.

Ferroalloy Production Capacity

For chromium and manganese, promotion of diversification of the supply of minerals from the ground is only a partial solution. These metals are generally processed into intermediate products, ferrochromium and ferromanganese, before they are used in the production of steel. A strategy for diversification of supply should consider whether the processing of these ferroalloys is also to be diversified or whether domestic processing of the ores into their alloy form is to be encouraged.

For a variety of reasons, including the use of newer facilities, lower labor costs, reduced transportation costs, and various forms of local government assistance, processing of ores into ferroalloys at or near the mine site has made major inroads into what was once a strong U.S. industry. This is a matter of some concern, that extends beyond the specific interests of the ferroalloy industry, because domestic ferroalloy processing facilities provided a capacity for quick response to interruptions in the supply of imported minerals. If one source of minerals should be cut off, it would be necessary only to expand foreign mine production elsewhere, not to increase capacity of ferroalloy plants as well. With decline of U.S. capacity, it would become more difficult and expensive to maintain production of ferroalloys for steel and stainless steel production in the event that supplies from one of the major producers were interrupted.

In the near term there are no technological fixes to improve the competitive state of the U.S. ferroalloy producers. If domestic capacity is to be maintained, assistance must be of a political or economic nature instead. In the longer term, however, there are several opportunities to increase the competitiveness of the U.S. industry. The U.S. Bureau of Mines could support development of improved technology for existing facilities in order to increase labor productivity and conserve energy and materials. Such improvements, though incremental, could help U.S. facilities compete with more modern facilities overseas. The Government could extend a greater degree of support, largely through policies targeted to encourage investment by U.S. firms to modernize their operations with new processes for the production of ferroalloys. Such processes, which are expected to produce substantial improvements in energy conservation, will be used in new foreign facilities and, to be competitive, U.S. firms must adopt them as well.

Substitution Alternatives

Substitution offers considerable potential to reduce U.S. materials import vulnerability with respect to chromium and, to a lesser degree, cobalt. However, because of the satisfactory performance, reasonable cost, and familiarity of chromium and cobalt containing alloys, there has been little interest in developing, testing, certifying, or using substitutes.

There are three major opportunities for the Government to improve the materials vulnerability status of the United States through substitution:

1. by making information about substitutes widely available to consumers, thus promoting and speeding the adoption of substitute materials;
2. by developing, testing, and, where required, certifying new materials lower in chromium and cobalt content for use in a limited number of industrial applications that account for large fractions of the critical applications for these materials; and
3. by supporting the development of advanced materials, including ceramics, composites, and unconventional metallic compounds, through basic and applied research, education, and the development of design and testing methods appropriate for the new materials.

Substitution Information Systems

During times of chromium or cobalt supply interruptions, interest in substitute materials rapidly increases. However, the period of time required to identify possible substitute materials, test them for particular applications, and modify production techniques for the substitute materials can be quite long. During this period of adjustment, consumers continue to demand these metals, drawing down the available supplies, and resulting in high prices and depletion of producer and consumer inventories. If the shortage is severe, the Government may be forced to allocate supplies to essential applications to the detriment of other industries and consumers. A system that helps users quickly identify and adopt substitutes could reduce the need for strategic materials, particularly in nonessential applications, thereby freeing materials from suppliers and in consumer inventories for use in essential applications.

To be useful, a substitution information system must reflect the needs and concerns of industrial consumers, but, because of its importance to the Nation as a whole as a means of reducing materials supply vulnerability, the Government has a major interest in establishing it. The system would describe current uses of strategic materials, identify the promising alternative materials, and maintain information on the performance of the substitutes and other information users need to determine how to adopt the substitutes.

Although supported by the Government, major elements of the system could be conducted by private sector participants (materials and testing professional societies, trade associations, universities, and individual industries) under Government-established guidelines.

Commercialization of Alternative Alloys

During World War II, the Government established a system of National Emergency Steels for use by industry when shortages of raw materials made it impossible to meet demand for the alloys then in use. Now, laboratory research has identified a number of promising alloys that could become substitutes for the high chromium and cobalt alloys in use today. These alloys are not ready for commercial use because they require further testing in the laboratory, evaluation of production techniques, and evaluation of performance in actual operating conditions. Since these testing and evaluation procedures may take a number of years and several million dollars to complete, the alloys are not "on the shelf," ready to be used in times of emergency. These alloys do hold promise for reducing the need for chromium and cobalt in critical applications, however. The Bureau of Mines, the National Laboratories of the Department of Energy, NASA, the Defense Department, and the National Bureau of Standards could direct efforts toward testing and evaluation of a limited number of alternative alloys where the potential for strategic material substitution is greatest. To be effective, such an effort would need to have the participation of industry to identify the alternative alloys to be evaluated. This approach is most promising for a number of applications that now use stainless steel. Alternative alloys, low in cobalt, are also possible in superalloy applications, but the high cost of testing and qualification could push costs of a comprehensive program to develop alternatives to the dozens of cobalt-containing superalloys now in use into the hundreds of millions of dollars.

Encourage Development of Advanced Materials

Ceramics, composites, and unconventional metallic materials have properties that suggest they might serve as substitutes for conventional materials that require strategic metals. Basic and applied research is still needed to overcome undesirable characteristics present in the materials and difficulties in the processing of raw materials and the manufacture of components. In addition, design methodologies for use of the materials must be developed to emphasize their advantages and minimize their disadvantages. Finally, up-to-date knowledge of the materials and the associated design and manufacturing technologies must be disseminated to potential users. Three separate activities could further these efforts:

1. *Coordinate Federal Advanced Materials R&D:* Research and development on advanced materials is conducted in many parts of the Government, but coordination is achieved largely through personal contacts and professional societies. Programs are developed in response to individual agency objectives, resulting in fragmentation and overlap of research efforts. Although it would be detrimental to attempt to control rigidly all research in advanced materials, increased interagency coordination toward common goals could improve the effectiveness of Government research and speed advances in understanding these new materials. Coordination of Government research is a responsibility of the executive branch, but Congress could further the coordination of Federal research on advanced materials through oversight of the progress of the Administration in preparing its report on the status of Government R&D in advanced materials. Such a report could also raise the visibility of Federal work on advanced materials, resulting in improved coordination with private industry and academic research.
2. *Improve Understanding of Advanced Materials:* Unlike direct substitutes, which may be used in place of current materials with little modification of designs or manufacturing processes, advanced materials will require designs and processes to be developed around their specific properties. This means that academic institutions, professional organizations, and individual firms need to develop programs to train engineers and designers in the proper selection and use of advanced materials. The Federal Government can assist in developing these education programs by providing grants for the hiring of new faculty, acquisition of new laboratory equipment, and design of curricula emphasizing advanced materials.
3. *Develop Testing and Certification Procedures for Advanced Materials:* Reliability and predictability are essential for any engineering material. Until a large body of information on the properties of advanced materials is developed in the laboratory and in the field, industry will not adopt the materials. The same is true for any new material; but in the case of advanced materials the barriers are likely to be greater and the delays longer because testing methods and certification procedures that reflect the special qualities of the materials, and the new design and manufacturing processes that will develop around them, do not yet exist. These barriers could be lessened if Government, industry, and academia focus on developing data on the properties of advanced materials, establish appropriate testing methods, and direct attention to certification procedures to ensure that advanced materials are not restricted from some applications unnecessarily. One approach could be the establishment of a nonprofit center associated with a testing society, professional organization, or academic institution under partial Federal sponsorship for the purpose of overcoming barriers to the use of advanced materials resulting from lack of data as to material properties.

Conservation Approaches

Conservation offers a number of ways to reduce U.S. dependence on foreign sources of supply of chromium, cobalt, manganese, and platinum group metals. In many cases, conservation opportunities are already being implemented, and others are under evaluation by private industry. In the case of manganese, it is likely that improvements in steelmaking technology will continue so that U.S. requirements for imported manganese will decline sharply. Recycling of catalytic converters is just beginning, and several major firms are considering opportunities to expand into this area. Recovery of chromium and cobalt from steelmaking, industrial, and chemical waste has begun to rise in the past few years, driven in part by Federal laws and standards on air and water quality and disposal of waste. Other opportunities are less likely to go forward under normal conditions. Superalloy scrap from obsolete aircraft components, a significant and reliable source of cobalt and chromium, is not likely to be used in the production of new superalloys so long as low-priced metal from foreign sources makes it economically unattractive to invest in the development of new recycling systems.

The promise of conservation of strategic materials—even from those practices already underway—is not assured. The strategic materials recycling industry is new, and our understanding of it is incomplete. Three approaches to improve the prospects for conservation of strategic materials are discussed below.

Update Information on the Recycling of Strategic Materials

Data on the generation and flow of scrap containing strategic materials is incomplete and out of date. The United States is poorly prepared to utilize scrap as a source of strategic materials in times of emergency. With more complete and detailed information, the Government could develop more effective R&D programs to enhance scrap recovery. Congress could direct the Bureau of Mines to conduct, and update on a regular basis, surveys of the generation and disposal of scrap containing chromium, cobalt, manganese, and platinum group metals. Information from these surveys would be useful in planning Government R&D efforts, in updating requirements for the national defense stockpile, and in identifying investment opportunities for private businesses.

Identify Specific Government Actions to Support Recycling of Strategic Materials

In recent years, a number of Federal actions affecting air and water quality and waste disposal have encouraged increased recycling. The potential effects of Government actions on recycling are beginning to receive consideration by policymakers. For example, Government-established freight rates on scrap—previously set at a level higher than the rates for shipping raw material—have been reduced.

The 1980 National Materials and Minerals Policy, Research and Development Act directed the Administration to assess the effects of Federal policies that affect all stages of the materials cycle, including recycling and disposal. A number of recycling activities are new and their economics have not been tested commercially. In some cases these activities may be affected substantially by Government policies. These recycling activities include the recovery of PGMs from catalytic converters, recovery of chromium and cobalt from industrial and chemical wastes, recovery of cobalt from spent hydroprocessing catalysts, and recovery of cobalt and other metals from cemented carbide scrap. Because these recycling industries are small or nonexistent, the effects of Government actions on the recovery of strategic materials from waste or scrap is generally ignored. Yet these sources, combined, could be important supplements to imports of chromium, cobalt, and platinum.

Congress could improve the outlook for conservation of strategic materials by requesting that the Administration identify opportunities to promote the recycling of strategic materials, identify barriers to new or increased recycling, and recommend to Congress ways to structure taxation, procurement, environmental, and other policies to encourage increased recycling. Such a study could be conducted by the Department of Commerce as part of its series of evaluations of strategic materials issues and U.S. industries.

Develop Recycling Technology for Superalloy Scrap

Scrap from processing of superalloys and from obsolete aircraft engine components could provide a secure source of material containing cobalt and chromium metal. At present, only a portion of this supply is reused in superalloys. The remainder is either downgraded to less demanding uses (often completely wasting the cobalt content), exported for use in other countries, or disposed of as waste. Several technical processes to recover individual metals from superalloys have been developed, but so far have only been tested in the laboratory.

The capacity of the United States to respond to cobalt supply disruptions could be enhanced if the Government were to put "on-the-shelf" one or more of the new superalloy recycling technologies by scaling the process up to a demonstration plant. Although relatively costly, on the order of $10 million, such a plant could make available the technology to recover high-quality cobalt from nearly all forms of superalloy scrap. This source was estimated to contain 4 million pounds of cobalt in the year 1980, making it equivalent to several opportunities for domestic mineral production. Estimates of the cost of metals produced from these recycling systems are proprietary, but are said to be in the range of $15 to $25 per pound of cobalt, which is in the same price range as domestic cobalt production.

CHAPTER 2

An Introduction to Materials Import Vulnerability

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CHAPTER 2

An Introduction to Materials Import Vulnerability

The United States, despite its wealth of resources, is a substantial importer of materials for industry. To some observers, the Nation's reliance on these imports constitutes a dangerous dependency, threatening a "materials crisis" more devastating than the recent energy crisis. Others see the U.S. position as quite manageable, though not without dangers and difficulties.

U.S. reliance on foreign sources for a number of important nonfuel minerals is not new nor, in itself, a cause for alarm. What really matters is whether import dependence makes the United States vulnerable to a cutoff of supply and whether that cutoff could have very damaging effects. In the past few years, these possibilities have raised a wave of concern. Undoubtedly, one factor in the crescendo of concern was the success of the OPEC cartel in controlling oil production during the 1970s, raising the world oil price to unheard of heights, and—at least temporarily—reducing oil exports to the United States for political reasons.

Today, many people believe that the United States is vulnerable to disruptions at least as serious as the oil crisis because of the nature, level, and sources of U.S. materials imports. Some fear that worse times are in store: they are persuaded that the Soviet Union is conducting a "resource war" against the United States and its allies, with the threat of shutting off supplies of minerals from central and southern Africa that are vital to U.S. national defense and basic industries.

Others familiar with minerals issues believe, on the contrary, that the interdependence policy for minerals supply has served the Nation well over the years and that the costs of self-sufficiency would be extremely high. Those who take this view concede that the supply of some imported materials could be interrupted, but count on flexible responses of the market economy—e.g., alternate suppliers, substitutions in use, and shifts from less to more essential uses—to compensate tolerably well for supply cutoffs or dislocating price increases.

There is some common ground in the opposing views. Both sides favor stockpiling imported materials that are vital to national defense and essential supporting industries as an insurance against supply interruptions. Both agree that, for at least a few imported minerals, continuity of supply is a serious question deserving a carefully considered government response.

The short list of these generally agreed upon "strategic" materials includes chromium, cobalt, manganese, and the platinum group metals (which comprise platinum, palladium, rhodium, iridium, osmium, and ruthenium). All of the four have essential uses, including military uses, for which there are no readily available substitutes—or in some cases, no substitutes even in sight. For all of them, production from domestic mines is negligible at best. Instead, these minerals are imported, mainly from a very few countries in the politically unstable region of central and southern Africa, an area that, along with the Soviet Union, holds most of the world's known resources of these important minerals.

Thus, for a few specific materials at least, most observers agree that the United States is in a vulnerable position. To shed light on the dimensions of this vulnerability, this chapter looks at the significance of imported materials in general to the United States and its allies and discusses those factors that led to the selection of chromium, cobalt, manganese, and the platinum group metals for in-depth assessment in this report.

The Importance of Nonfuel Minerals Imports

In terms of dollar value in world trade, U.S. reliance on imports of nonfuel minerals is moderate. The United States is still a leading world minerals producer as well as the world's largest minerals consumer. In 1981, as the dollar rose against other currencies, U.S. imports of nonfuel minerals (raw and processed) amounted to $17.6 billion, exports were $28.8 billion, and thus net imports were $11.2 billion, a moderate sum when compared to U.S. net energy imports, which were $75 billion.[1]

The overall figures, however, aggregate a great many unlike materials, from scrap steel to gem and industrial diamonds to fertilizers. It is particular kinds of minerals—materials needed for basic industry and vital ingredients for military hardware—that are the center of concern. Figure 2-1 shows the extent of U.S. reliance on imports of 34 important nonfuel minerals and metals as of 1980. Nearly all of the manganese, bauxite, cobalt, tantalum, and chromium used in the United States is mined in foreign countries. Imports of other important minerals—the platinum metals group, asbestos, tin, nickel, zinc, cadmium, and tungsten—range from 85 to 50 percent of U.S. consumption.[2] Even iron ore, once supplied wholly by domestic mines, now comes in substantial amounts from foreign mines. As table 2-1 shows, import dependence was high 30 years ago for much the same list of minerals that is the focus of concern today: In 1952, foreign mines provided 70 to 80 percent of the Nation's bauxite, manganese, and tungsten, and 90 to 100 percent of its platinum, cobalt, nickel, and chromium.[3]

Table 2-1.—U.S. Dependence, Selected Minerals, 1950-82 (net imports as percent of apparent consumption)

	1950	1970	1979	1980	1981	1982
Bauxite[a]	71	80	93	94	94	96
Chromium	100	100	90	91	90	85
Cobalt	92	96	94	93	92	92
Copper	35	8	13	16	6	1
Iron ore	5	30	25	25	22	34
Lead	59	40	5	0[b]	1	3
Manganese	77	94	98	98	99	99
Nickel	99	91	75	76	75	76
Platinum	91	98	89	88	84	80
Tungsten	80	40	58	53	50	46
Zinc	37	60	63	60	64	58

[a] 1979-82, includes alumina.
[b] Net export.

NOTE: Net imports = imports - exports + adjustments for government and industry stock changes.

SOURCE: **1950, 1970:** *Report of National Commission on Material Policy*, June 1973, pp. 2-23. **1979-82:** U.S. Department of the Interior Bureau of Mines, *Mineral Commodity Summaries 1984*.

It is worth noting the modest dollar value of many of the materials for which the United States is most import dependent. For example, the entire year's bill for 1981 imports of cobalt, chromium, and manganese was between $230 million and $300 million apiece—equivalent to 1½ days (at most) of oil imports. The fact that the quantities involved are relatively small and total costs low does not imply that imports of these materials are insignificant; some are vital. It does imply that even a sharp rise in price for the materials might have no great effect on the economy as a whole (a point to keep in mind later, in the discussion of possible cartel control). It also indicates that stockpiling these materials, as a way of assuring a reliable supply, can be practical and relatively inexpensive.

Changes in Amount of Imports

U.S. minerals imports increased from 1950 to the 1980s, but at a modest pace overall, and not uniformly for all minerals. (Import dependence as a percentage of U.S. consumption for platinum, nickel, and chromium declined, mostly because of recycling.) In general, the gradually rising flow of imported minerals into the United States reflects lower prices of foreign materials, often because the ores being

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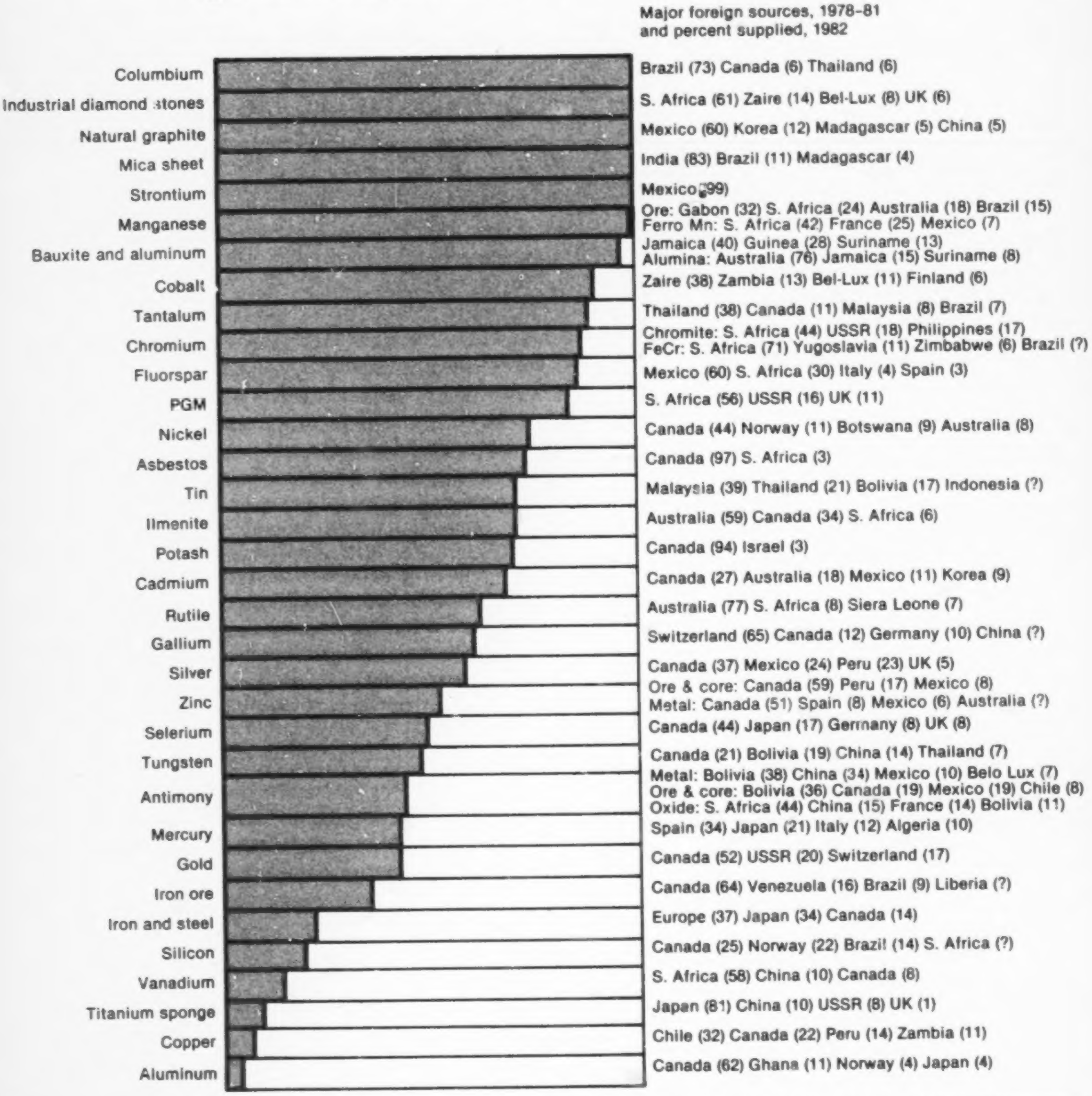
[1] Unless otherwise noted, data on production, consumption, and imports of nonfuel minerals comes from the Bureau of Mines, Department of the Interior. Energy data was provided by the Department of Energy.

[2] "Consumption" here means apparent consumption, which is domestic primary production, plus recycled materials and net imports, adjusted to reflect releases from or additions to industry or government stocks.

[3] The President's Materials Policy Commission, *Resources for Freedom* (Washington, DC: U.S. Government Printing Office, 1952), vol. 1, pp. 6 and 157.

Figure 2-1.—Net Import Reliance As a Percent of Consumption, 1982



NOTES: Net import reliance is figured as percent of apparent consumption, except for rutile, for which net import reliance is figured as percent of reported consumption.
Net imports = import - exports + adjustments for government and industry stock changes.
Apparent consumption = U.S. primary and secondary production + net imports.

SOURCE: U.S. Department of the Interior, Bureau of Mines.

mined abroad are richer, although other factors such as lower labor costs or government subsidies may also be important. The U.S. minerals economy is managed, on the whole, by a great many private businesses looking for the best deal they can get.

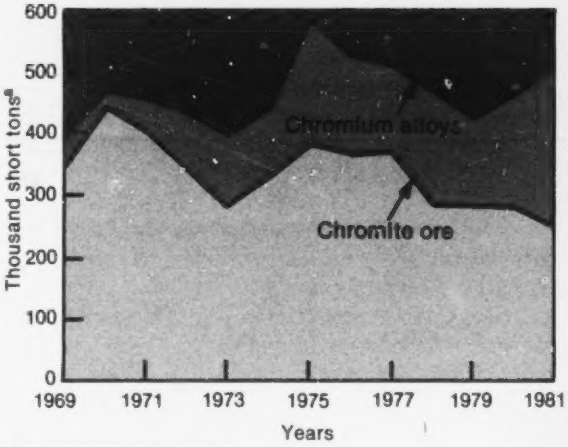
Changes in Use of Imports

While nonfuel minerals imports of the United States have slowly risen, significant changes in the uses of imports have taken place. Growth has occurred in selective demand for specialty steels using chromium, for high-strength, high-temperature superalloys using cobalt and chromium, and for cobalt catalysts. Also, in the 10 years from 1970 to 1980, annual consumption of cobalt for superalloys (which are particularly important for aerospace applications, military and civilian) roughly tripled, rising from about 2 million to over 6 million pounds. Use of cobalt in catalysts quadrupled. Platinum group consumption jumped from 1.4 million troy ounces in 1970 to 2.2 million in 1980, of which more than 700,000 troy ounces went for catalytic converters to control pollution from automobile exhausts. Use of platinum as a catalyst in petroleum refining has also grown, rising from less than 40,000 troy ounces in 1960 to 171,000 in 1980. In the severe worldwide 1981-83 recession, U.S. consumption of all these metals declined, but recovery is now in evidence.

Changes in Form of Imports

Nonfuel mineral imports are no longer mostly in the form of raw ores. Instead, minerals-producing countries like South Africa are now taking advantage of their lower wages, proximity to raw materials, cheaper energy, and modern new processing facilities, to export processed materials such as ferroalloys[4] rather than chromite and manganese ores. Figures 2-2 and 2-3 show how rapid this change to importation of ferroalloys has been. The United States now imports 35 to 50 percent of its chromium in ferroalloy form, compared with 8 to 12 percent a decade ago. Ferromanganese and refined manganese metal now account for 60 to 75 percent of manganese imports; at the beginning of the 1970s they amounted to only 20 percent of the total. As part of the same process, the domestic ferroalloy industry has shrunk remarkably, from production levels of 2.6 million to 2.8 million tons in the peak years of 1965 to 1970, to 1.5 million tons in 1981 and an estimated 800,000 tons in the recession year of 1982.

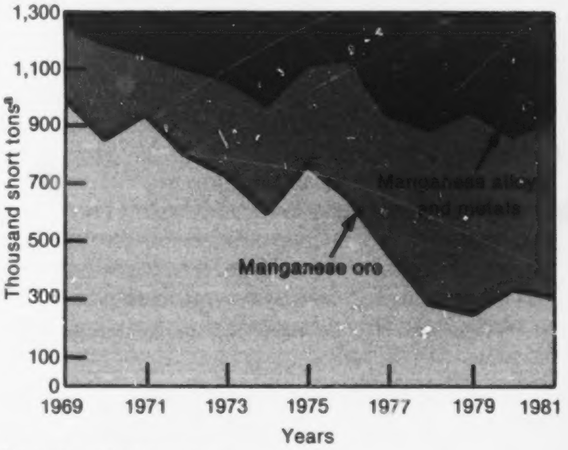
Figure 2-2.—U.S. Imports of Chromite Ore and Chromium Alloys[a]



[a]Tons of contained chromium.

SOURCE: U.S. Bureau of Mines data.

Figure 2-3.—U.S. Imports of Manganese Ore and Manganese Alloys and Metals[a]



[a]Tons of contained manganese.

SOURCE: U.S. Department of the Interior, Bureau of Mines data.

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[4] Alloys of iron and other elements, used as raw material in the production of steel; e.g., ferromanganese and ferrochromium.

This has led to concern that if international trade were restricted or disrupted, it might be difficult to replace lost supplies of ferroalloys with imports of chromium or manganese ores from other sources, because of the lack of U.S. facilities to process the ore into ferroalloys. Similarly, if a major high-grade deposit of chromium or manganese were discovered, we might not have the production capacity to produce ferroalloys until facilities were expanded, which could take several years.

Definition and Selection of Strategic Materials

One of the greatest difficulties in assessing import vulnerability lies in defining what materials are strategic. There is no fixed, universally accepted definition of the term "strategic material." Much depends on the purpose of the definition. For purposes of a national stockpile,[5] present U.S. law defines "strategic and critical materials" in the context of a hypothetical, complete cutoff of foreign supplies during a 3-year national emergency. The Strategic and Critical Materials Stock Piling Revision Act of 1979 (Public Law 96-41) says:

> The term "strategic and critical materials" means materials that (A) would be needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency, and (B) are not found or produced in the United States in sufficient quantities to meet such need. The term "national emergency" means a general declaration of emergency with respect to the national defense made by the President or by the Congress.

In the context of broader materials policy, former Secretary of the Interior James B. Watt gave the term "strategic" a more elastic meaning. In 1981 testimony before the House Subcommittee on Energy and Mineral Resources, he said:

> It is not my intention to limit the word "strategic" to its former definition of minerals wholly or substantially from foreign sources. We must acknowledge, as an element of minerals policy, that all minerals are strategically important in a complex industrial society.[6]

By this definition, however, every element of production—land, energy, labor, capital, technology—is also essential and therefore strategic, and the term becomes so broad as to lose any practical meaning. Moreover, a definition of strategic materials as all those that are "wholly or substantially from foreign sources" is not widely accepted. First, it leaves out the element of critical needs for particular materials. Then, it seems automatically to equate import dependence with vulnerability. Many materials analysts do not accept this equation as a guide to policy decisions.[7] Moreover, it runs counter to a major shared conclusion of the materials commissions that have reported to three American Presidents over the past 30 years; that is, that the Nation should seek materials wherever they may be found, at the least cost and consistent with national security and the welfare of friendly nations.

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[5] Current stockpile planning is based on the military, industrial, and essential civilian requirements of the first 3 years of a major conflict, assuming that austerity measures are taken to sustain defense production.

[6] U.S. Congress, Senate Committee on Energy and Natural Resources, Subcommittee on Energy and Mineral Resources, *Hearings on Strategic Minerals and Materials Policy*, 97th Cong., 1st sess., Apr. 1, 1981, p. 4.

[7] See, for example, Congressional Research Service, *A Congressional Handbook on U.S. Materials Import Dependency/Vulnerability*, Report to the Subcommittee on Economic Stabilization, Committee on Banking, Finance, and Urban Affairs, House of Representatives, 97th Cong., 1st sess., September 1981, p. 7, p. 341 ff; Hans Landsberg and John E. Tilton, "Nonfuel Minerals," in *Current Issues in Natural Resource Policy*, Paul R. Portney with Ruth B. Haas (eds.) (Baltimore: The Johns Hopkins University Press, 1982); Robert Legvold, "The Strategic Implications of the Soviet Union's Nonfuel Minerals Policy," paper prepared for the School of Advanced International Studies, The Johns Hopkins University, May 1981.

In its 1981 Preliminary Assessment of strategic metals, the Materials Forum of the United Kingdom discussed the term "strategic" in this way:[8]

> The term "strategic minerals" has traditionally been used in the United Kingdom to refer to those minerals which are vital to the national defense and yet have to be procured entirely or in large part from foreign sources. However, in this country, "strategic" no longer has a mere defense connotation when attached to minerals; it has come to have a wider meaning, somewhat obscure, and A. A. Archer of the Institute of Geological Sciences in London has recently shown how this can be clarified.
>
> He believes it is useful to distinguish some minerals from others by disengaging two main strands. One is, that some minerals are more important, vital, essential or critical than others because they make a demonstrably greater contribution to the national well-being, so that interruption or cessation of supplies, from whatever source, would have graver consequences. This can be described as the degree of "criticality" of a mineral. The other strand is the "vulnerability" of supplies to interruption; some minerals have sources which may be judged to be more vulnerable than others. Although the concept of vulnerability is mainly linked with imports, the possibility of the disruption of domestic supply cannot be entirely overlooked.

The concepts set forth above are used in this report as the basis for a definition and selection of strategic materials.

Not surprisingly, both the selection of criteria and the screening of materials against the criteria involve a good deal of qualitative judgment. OTA's assessment uses quantitative measures as much as possible. Also, it builds on the earlier efforts of others to define and list strategic materials. (See app. A.) In the end, however, any list of strategic materials must reflect the judgment of its authors.

Criticality

The criticality of materials has to do with how they are used. Three main factors are part of the concept:

- Essential use for national defense.
- Essential use for industry.
- Lack of suitable substitutes.

Essential use for national defense means that, without the material, the Nation's capacity to defend itself could be seriously compromised. Examples of material uses that are vital to national defense are cobalt in superalloys for jet engine turbine blades and discs, where resistance to heat under conditions of high stress is necessary; or chromium for jet engines, to withstand hot corrosion and oxidation; or the manganese used industrywide in steelmaking to eliminate faults in steel that arise from sulfur content.

Essential use for industry is another main factor. Use of the materials must fill such an important need that without it, industries that are basic to the Nation's economic well-being and to military production could be crippled.

Materials vital to national defense are likely to be essential for industry, as well, in the same or other applications. Industrial machinery is a prime example. The machine tools that shape, stamp, cut, and drill all metal goods, military and civilian, are made of manganese-bearing steel. The best binder for carbide cutting tools and drill bits is cobalt. Another example is in the aerospace industry, where jet airplanes for civilian use have much the same material requirements as do military planes.

Industrial uses for some critical materials cover a broad spectrum, ranging from virtually indispensable to nonimportant. Chromium is an example: stainless steel cannot be made without it. Of the hundreds of industrial uses for stainless steel, some—e.g., automobile bumpers or hub-caps—are easily replaceable; for others—e.g., corrosion-resistant pipes in oil refineries—nothing else now available serves as well.

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[8] The Materials Forum, *Strategic Metals and the United Kingdom: A Preliminary Assessment*, published by the Institution of Mechanical Engineers, July 1981, p. 3.

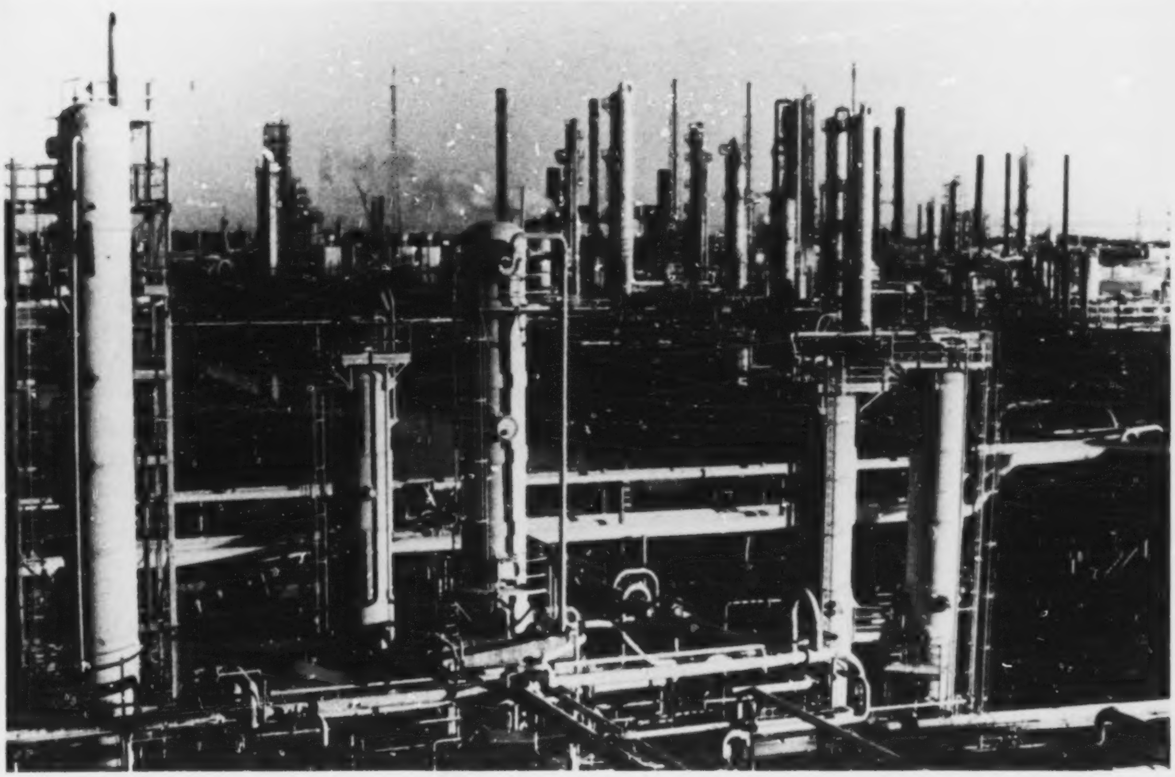

Photo credit: American Petroleum Institute and Exxon Corp.

Petroleum refiners are major consumers of strategic materials in steel, stainless steel, and processing catalysts

Closely related to the concept of essential use is the *lack of suitable substitutes*. This implies that substitutes, if available at all, either cost much more or involve important sacrifices of properties or performance. In a few cases (e.g., chromium for corrosion resistance) there may be no real alternative at present levels of technology in some critical industrial and defense applications.

One aspect of substitution is simply the replacement of one material for another—nickel for cobalt, for example, in some superalloys. Some of these substitutions replace one critical metal with another. Of obviously greater value is the replacement of a scarce material with an abundant one—advanced ceramics for instance, may be a long-term replacement for metal superalloys.

The economic dependence of the Nation on particular materials is sometimes mentioned as a factor in criticality. One of the conventional measures of economic importance—the dollar value of the material consumed or imported per year—is not a useful criterion for critical function. Several materials that have esssential uses but no substitutes readily available are quite low in dollar value; for example, net imports of cobalt, chromium, and manganese each ran about $230 million to $300 million in 1981—a drop in the bucket in a $3 trillion-per-year economy. Yet even a partial loss of supplies of these materials could have serious effects on production, jobs, and the survival of business firms in the many industries where their uses are essential (e.g., steel, aerospace, and automotive industries).

Exactly how much the economy as a whole would suffer from a sudden drop in the supply of specific critical materials is hard to calculate. Cranking figures on supply loss through an economic input-output model may appear to be systematic and objective. But such models can produce highly unrealistic results if they make no allowance for compensatory moves by users of the material in question.[9] Studies of chromium and cobalt shortages are worth noting at this point.

The National Materials Advisory Board (NMAB) (of the National Academies of Science and Engineering) in its 1978 study of chromium conservation opportunities, concluded that about one-third of U.S. chromium use could be quite promptly replaced in an emergency. Without specifying any dollar figures, the study observed that replacing a chromium shortfall of this magnitude would "not have serious economic consequences on industrial dislocations."[10] The study also refrained from estimating the economic costs of a greater shortfall cutting into uses which could *not* be quickly replaced; obviously the effects of such a shortfall would be greater.

In its 1982 study of cobalt, the Congressional Budget Office reported cost estimates of a cobalt supply cutoff that took into account the buffering effects of private stocks, materials substitution, scrap recovery, and alternative suppliers.[11] The Department of the Interior provided a range of cost estimates, depending on various political assessments. The most extreme case (considered highly improbable) involved a 2-year shortfall (in 1985-86) from both Zaire and Zambia. In this extreme case, U.S. cobalt consumption was expected to drop 20 percent in 1985 and 35 percent in 1986—but with little loss in economic output, mainly because of substitution. Extra costs to the economy (in terms of higher prices) were estimated as $1 billion for 1985 and $1.8 billion for 1986 (in 1980 dollars). A Commerce Department study, which assumed a 75-percent reduction in output in Zaire and Zambia in 1985, came to similar conclusions: 23 percent lower cobalt consumption, forced substitution, little lost output. Extra cost to the economy of high cobalt prices was estimated at $2.5 billion—assuming a cobalt price of $112 per pound (more than twice as high as the top price during the cobalt price spike of 1978-79, and over 20 times the 1982 price). The inflationary pressure of this price increase was reckoned as no more than 0.1 percent in the economy as a whole.

Analysis of the effect of material shortfalls on the economy as a whole is at an early, unrefined stage.[12] In addition, because these economic effects are a reflection of the essential nature of the material's uses and the lack of substitutes, it seems needlessly complex to add "economic effects" as another criterion of criticality. Thus, for the purpose of this chapter, which is to select a list of strategic materials for study, no attempt was made to quantify the economic effects of losing a part or all of the supply of candidate materials. Rather, economic effects were simply kept in mind as a part of the meaning of criticality.

Vulnerability

Among the conditions that affect supply vulnerability, a most important factor is *lack of diversity of supply*. Reliance on a sole supplier, even a highly reliable one, can be risky. Of the few significant interruptions in U.S. materials supply in the past 30-odd years (described in ch. 4), the most disruptive was probably the loss of nickel from Canada during the 4-month nickel strike in 1969. Canada was at that time the source of 90 percent of new (nonrecycled) U.S. nickel supplies.

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[9] Hans H. Landsberg, "Minerals in the Eighties: Issues and Policies: An Exploratory Survey," paper prepared for the Oak Ridge National Laboratory, Oak Ridge, TN, 1982, pp. 30-31.

[10] National Materials Advisory Board, *Contingency Plans for Chromium Utilization*, NMAB-335 (Washington, DC: National Academy of Sciences, 1978).

[11] Congressional Budget Office, *Cobalt: Policy Options for a Strategic Mineral* (Washington, DC: U.S. Government Printing Office, 1982), pp. 21-24.

[12] A recent attempt to quantify economic effects of materials supply disruptions, using a neoclassical econometric model of the primary metals industry is reported by Michael Hazilla and Raymond J. Kopp, "Assessing U.S. Vulnerability to Mineral Supply Disruptions, An Application to Strategic Nonfuel Minerals," paper prepared for Resources for the Future, Washington, DC, draft May 5, 1982.

U.S. imports of critical minerals are part of the nexus of world trade in these commodities. If one of its usual suppliers fails for some reason to produce, the United States can buy elsewhere as long as alternate producers exist (although probably with some shortage and delay, since mining companies often commit supplies to their customers considerably in advance and it takes time to expand capacity). Thus, the total number of producers in the world for particular minerals is important, and so are their relative shares of production. If one or two countries dominate (as South Africa and the Soviet Union do for PGM), the potential for disruption is greater than if there were a number of substantial producers.

In the same way, diversity in the location of mineral reserves is important for the future. Since reserve estimates change dramatically over time with new technology, new discoveries, and price changes, they are a rough indicator of where to expect minerals production.[13]

By the measure of reserve location, it appears that world production of certain important minerals could become more concentrated than it is now. For example, South Africa and the Soviet Union produced 64 percent of the world's manganese in 1982; they own 77 percent of the reserves. South Africa today produces 22 percent of the world's chromite ore, but holds 91 percent of the reserves (see ch. 5 for further discussion).

In general, reliance on one or a very few suppliers creates the potential at least for cartel action to limit supplies and raise prices, for politically inspired embargoes, or for a cutoff of supply due to local disturbances in the producer countries. Of these possibilities, discussed in some detail in chapter 4, the last appears most likely.

Instability in foreign sources of supply is certainly an element in vulnerability. The only way to evaluate instability in particular countries is by qualitative judgment, and opinions differ. For example, some consider South Africa a risky source because they see an inherent instability in minority rule by 4.5 million whites of 20 million blacks.[14] Some of those concerned about a "resource war" fear that the Soviets or Soviet-backed forces may seize power in South Africa, and the Soviet Navy interdict shipments of critical materials from South African ports.[15] Others see such an interdiction of trade as virtually an act of war, and do not consider it likely, short of a shooting war.[16] A quite different point of view is that South Africa has proved to be one of the world's most reliable suppliers, with a record of long-range planning and steady production, and a conservative commercial approach that rules out political embargoes.

There is greater consensus that production of minerals in the relatively new African nations could be disrupted by local wars, insurrection, or civil disorder, or by inexperienced management of complex minerals enterprises—regardless of the part the Soviet Union might play in aggravating these dangers (see ch. 4 for a discussion of these possibilities).

Other developing countries also may be subject to political instability, thus affecting minerals production. Indonesia (a significant supplier of tin) was governed less than 20 years ago by the strongly anti-Western Sukarno, and Thailand (an important source of tantalum and tin) is under some pressure from its revolutionary neighbors. In Latin America, too, political upheavals have, on occasion, interfered with

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[13] "Reserves" comprise only part of a country's mineral wealth. They are deposits which are known and are technically and economically feasible to mine at a profit at the time the data is analyzed. "Resources" include reserves and all other deposits that are known but are not economic to mine, as well as deposits that are merely inferred to exist from geologic evidence. "Reserve base" includes resources that are currently economic ("reserves"), those that are considered marginally economic plus a portion of the subeconomic resources. Throughout this study, reserve data has been used for comparison purposes, unless otherwise noted.

[14] Robert E. Osgood, "The Security Implication of Dependence on Foreign Nonfuel Minerals," paper prepared for the School of Advanced International Studies, The Johns Hopkins University.

[15] Rear Adm. William C. Mott, "Introduction: What Is the Resource War?" *Strategic Minerals: A Resource Crisis* (Washington, DC: The Council on Economics and National Security, 1981), pp. 20-29.

[16] Osgood, op. cit.; Legvold, op. cit.

Photo credit: U.S. Air Force

Chromium and cobalt are essential in jet engines of high-performance military aircraft such as this U.S. Air Force F-16

minerals production and export. Cuba, for example, was considered a potential supplier of nickel for the United States, as a supplement to Canadian supplies. When the Communist government was installed in Cuba, access to this source was lost due to a U.S.-imposed embargo.

Another possible source of vulnerability is *long-distance transportation by sea*. The United States imports large tonnages of a number of important materials from distant countries by sea. For example, in 1981 the United States imported 3 million tons of alumina from Australia; some 640,000 tons of manganese ore, mainly from Gabon, South Africa, and Australia; and 800,000 tons of ferromanganese and ferrosilico-manganese, largely from South Africa, France, and Brazil. If sea lanes were blocked in a war, it is difficult to conceive how these large tonnages could be airlifted to the United States from the producer countries.[17]

Although import dependency does not equate with vulnerability, and domestic supplies are not an ironclad guarantee against disruption, the *lack of adequate domestic supplies* counts as a most important factor in vulnerability. Lagging investment and labor troubles have, on occasion, limited production from U.S. mines. Yet, at the very least, domestic supplies can be relied on in a national emergency, to meet part of domestic requirements, assuming the government would exercise special powers to keep production going.

"Lack" of domestic supply can be a relative term, ranging from resources that look promising now or in the near future (platinum in the Stillwater Complex in Montana) to subeconomic deposits (cobalt in the Blackbird deposit of Idaho) to resources of such poor quality (manganese in Minnesota and Maine) that they may never be economical to mine.

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[17] The payload of a C5A, our largest cargo aircraft, is about 100 tons. At that payload, it has a range of 2,500 miles.

Combining Both Strands: Defining "Strategic"

When the strands of criticality and vulnerability are combined, a definition something like this emerges: If a material's essential uses, for which there are no available economic substitutes, exceed the reasonably secure sources of supply, the material is "strategic." However, neither "essential uses" nor "reasonably secure sources of supply" can be defined with quantitative precision. The following section screens particular materials against the criteria described in this section, with the aim of selecting a few materials that nearly everyone can agree are "strategic" and that exemplify the problems and opportunities presented by these materials.

Selecting Strategic Materials

The group of materials chosen for screening for this report included the 86 nonfuel minerals for which the Bureau of Mines regularly publishes statistics.[18] The Bureau reports data for each material on the structure of the domestic industry; consumption (overall and by end use or industry); imports and exports, including sources of imports and how much each source supplies; purchased scrap recycling; events, trends, and issues relevant to the material; world production, reserves, and resources; and substitutes and alternatives. These kinds of data (drawn from the Bureau of Mines and other sources) were the basis for fitting materials against the criteria described earlier, defining which materials are strategic, and selecting them for further study. Table 2-2 lists the 86 materials that comprised the group chosen for screening.

Table 2-2.—Materials To Be Screened

Aluminum
Antimony
Arsenic
Asbestos
Barite
Bauxite
Beryllium
Bismuth
Boron
Bromine
Cadmium
Cement
Cesium
Chromium
Clays
Cobalt
Columbium
Copper
Corundum
Diamond (industrial)
Diatomite
Feldspar
Fluorspar
Gallilum
Garnet
Gem stones
Germanium
Gold
Graphite (natural)
Gypsum
Hafnium
Helium
Ilmenite
Indium
Iodine
Iron ore
Iron and steel
Iron and steel scrap
Kyanite and related materials
Lead
Lime
Lithium
Magnesium metal
Magnesium compounds
Manganese
Mercury
Mica (natural), scrap and flake
Mica (natural), sheet
Molybdenum
Nickel
Nitrogen (fixed) ammonia
Peat
Perlite
Phosphate rock
Platinum group metals
Potash
Pumice and volcanic cinder
Quartz crystal (industrial)
Rare-earth metals
Rhenium
Rubidium
Rutile
Salt
Sand and gravel
Selenium
Silicon
Silver
Sodium carbonate
Sodium sulfate
Stone
Strontium
Sulfur
Talc and pryophyllite
Tantalum
Tellurium
Thallium
Thorium
Tin
Titanium dioxide
Titanium sponge
Tungsten
Vanadium
Vermiculite
Yttrium
Zinc
Zirconium

SOURCE: Office of Technology Assessment, drawn from U.S. Department of the Interior, Bureau of Mines data.

One of the leading criteria for vulnerability was the sufficiency of domestic supplies of a material. The United States is a net exporter or is self-sufficient for 22, or approximately one-quarter, of the materals on the list (table 2-3). As a first cut in the screening, all these materials were eliminated from further consideration as strategic. In addition, 50 of the 86 materials on the original list are imported mostly from countries judged to be stable sources of supply—i.e., countries presently free

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[18] Unless otherwise noted the information presented is from the Bureau of Mines.

Table 2-3.—Materials for Which the United States is Self-Sufficient or a Net Exporter

Boron
Bromite
Clays
Diatomite
Feldspar
Garnet
Helium
Iron and steel scrap
Kyanite and related minerals
Lithium
Magnesium metal
Magnesium compounds
Mica (natural), scrap and flake
Molybdenum
Perlite
Phosphate rock
Quartz crystal (industrial)[a]
Sand and gravel
Sodium carbonate
Stone
Talc and pyrophyllite
Vermiculite

[a] Lasca is one of the three commodities reported in this category. It is imported, but the net import reliance is not available.

SOURCE: Office of Technology Assessment, based on U.S. Department of the Interior, Bureau of Mines data.

from threats of internal disturbances or outside pressure from forces hostile to the United States. These "stable" sources range from industrialized countries such as Canada and Australia to advanced developing nations, particularly Latin American ones such as Brazil, Chile, and Mexico. For most of the 50 materials in this group, there was either considerable diversity in sources of supply, or stability, or both. For these reasons, the vulnerability of the United States to disruption of the supply of these materials was judged to be relatively low. However, dependable allies or even the United States itself cannot be considered totally immune from interruption in minerals and metal production, as shown by the previously mentioned Canadian nickel strike.

The primary end uses of this group of materials were also scrutinized, to see whether the uses should be considered critical. For materials with significant military or important industrial uses, the availability of substitutes to replace these uses was checked. Combining qualitative judgments with quantitative information on both the vulnerability and criticality factors, it appeared that the critical uses of materials in this group did not exceed the amount imported from stable sources. Thus, they were screened out of the list of strategic materials candidates. Appendix B shows these 50 materials and their import sources.

It was not possible to eliminate as a group the remaining 14 materials. They required more detailed individual scrutiny. As the following discussion shows, at least four of them—chromium, cobalt, manganese, and the platinum group metals—clearly met all of the criteria set forth in the first part of this chapter and were definitely strategic:

- They are essential for the national defense and other important industries.
- For some of their essential uses no satisfactory substitutes are available.
- There is little or no production of any of these materials in the United States (although for some, recycling is significant).
- They are supplied largely by a very few countries in a politically unsettled region (central and southern Africa), and this same region, plus the Soviet Union, holds most of the world's known resources.

These four minerals form a "first tier" of strategic materials that have been selected for detailed treatment in this report. The remaining 10 materials share some characteristics of criticality and vulnerability with the first tier (as detailed in the discussion below), but in less definitive ways. While the materials in this second tier may be thought of as strategic to some degree, they are less so than those in the first tier. Table 2-4 shows the 14 materials grouped by first and second tiers.

Table 2-4.—U.S. Strategic Materials

First tier	Second tier
Chromium	Bauxite/alumina
Cobalt	Beryllium
Manganese	Columbium
Platinum group metals	Diamond (industrial)
	Graphite (natural)
	Rutile
	Tantalum
	Tin
	Titanium sponge
	Vanadium

SOURCE: Office of Technology Assessment.

Overview of Selected Strategic Materials

Agreement that chromium, manganese, cobalt, and the platinum group metals are strategic materials is widespread. The selections of strategic materials made by other authors, as described in the first part of this chapter, all include these metals. A brief explanation of the reasons for selecting these four materials follows, with an emphasis on the vulnerability strand. Chapter 3 summarizes in more detail the essential uses of the first-tier materials, probable trends in their consumption over the next 10 to 25 years, and the current status of substitutes for their uses. The discussion below presents data for each of the materials on U.S. consumption over the past 5 years and on several factors related to vulnerability: U.S. net import reliance, import sources, world production and reserves. Similar information about second-tier materials can be found in appendix C.

Chromium

Chromium (Cr) is a lustrous, hard, steel-gray metallic element found primarily in *chromite*, a black to brownish-black chromium ore ($FeCr_2O_4$). It imparts unique properties of corrosion resistance, oxidation resistance at high temperatures, and strength to other metals. An important ingredient in many steels and alloys, chromium is irreplaceable (at present levels of technology) in stainless steels and high temperature-resistant superalloys. And many of the uses of stainless steels and superalloys are essential, such as in jet engines, in other military applications, and in vital nondefense production.

Besides its metallurgical uses, chromium is essential in the chemicals industry, where it is used in making pigments and chromium chemicals. Chromite is used in making refractory bricks to line metallurgical furnaces; such bricks retain their strength and stability even when subjected to rapid, extreme changes in temperature, and are resistant to acid and alkali environments. Additional uses of chromium are in leather tanning, in wood treatment, and as additives to oil-well drilling mud.

Table 2-5 shows chromium consumption in the United States from 1978 to 1982, including the chromium contained both in chromite ore and in the semi-processed alloy ferrochromium. The sharp decline in 1982 reflects that year's recession, with the steel industry especially hard hit.

In the 1979-82 period, imports accounted for 85 to 91 percent of U.S. chromium consumption. Recycling of scrap amounted to 12 percent of apparent consumption in 1982. As table 2-6 shows, the largest supplier to the United States for both chromium ore and ferrochromium is South Africa. The Soviet Union is actually the world's largest producer of chromium, and once played a significant role in supplying the United States with chromium ore. Since the mid-1970s, however, its contribution to U.S. supplies has declined significantly. Other U.S. suppliers of chromium ore—e.g., the Philippines, Finland, and Turkey—have limited production capacity compared to South Africa's.

The recent trend among a number of ore producers has been to process the ore into ferrochromium. Zimbabwe presently exports most of its chromium as ferrochromium.

U.S. chromium resources are mostly in the Stillwater Complex in Montana, podiform de-

Table 2-5.—U.S. Consumption of Chromium, 1978-82

Year	Apparent consumption[a] (thousand short tons chromium content)	Net import reliance[b] (percent)
1978	590	91
1979	610	90
1980	587	91
1981	510	90
1982	319	85

[a] Apparent consumption = U.S. primary and secondary (recycled) production and net import reliance.

[b] Net import reliance = (imports - exports + changes in government and industry stocks) ÷ apparent consumption.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries*, 1983 and 1984.

Table 2-6.—Sources of U.S. Chromium Imports

Country	1979-82 (percent)	1982 (percent)
Chromite:[a]		
South Africa	48	59
Soviet Union	17	6
Philippines	13	11
Turkey	7	6
Albania	6	1
Finland	5	7
Madagascar	4	9
Ferrochromium:		
South Africa	61	35
Zimbabwe	12	25
Yugoslavia	12	12
Brazil	4	11
Sweden	4	4
Turkey	2	4
West Germany	2	3
Japan	1	—
China	1	4
Other	1	2

[a] Chromite = chromium ores.

NOTE: Major world producers of chromite and their contribution to world supplies in 1982 were: Soviet Union (34 percent); South Africa (22 percent); Albania (12 percent); Brazil (10 percent); Zimbabwe, Philippines, Turkey, and Finland (4 percent each); India (3 percent). See table 5-4 of ch. 5 for more detail, and for information on reserves.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook*, 1980, 1981, 1982, and 1983.

posits in California and Alaska, and beach sands in Oregon. These deposits are not considered close to being economically mineable at present. Some chromium would be produced as a co-product of nickel and cobalt at Gasquet Mountain in northern California, according to the plans of the developer. However, startup of this mine in the near future seems highly unlikely without either Government subsidies or substantially higher world prices for these metals. (Detailed information on domestic and world chromium production is covered in ch. 5.)

Cobalt

Cobalt (Co) is a hard, brittle metallic element found in association with nickel, silver, lead, copper, and iron ores. It resembles nickel and iron in appearance.

The largest and most critical end use of cobalt is in superalloys, used mainly in gas turbines (aircraft and land and marine-based) that require high strength at very high temperatures. Cobalt has no satisfactory substitute as a binder in carbide tools. It is a preferred ingredient in other steels and alloys as a hardening agent. Another application is in electrical equipment, where cobalt's strong magnetic properties make small, powerful, and long-lasting magnets. Cobalt is also used as a catalyst, especially in petroleum refining, to remove sulfur and heavy metals. Spurred by high cobalt prices in the 1978-80 period, considerable substitution for cobalt has occurred—e.g., ceramics in permanent magnets. But cobalt is still considered essential in many of its applications, especially in many superalloys.

Table 2-7 shows total annual consumption of cobalt. Quantities used are relatively small compared to materials such as chromium and manganese. A trend toward declining cobalt consumption is apparent since the price hike and fears of shortage in 1978 (see ch. 4).

The United States is highly import-dependent (92 percent) for cobalt, with the rest of demand supplied by recycling. The largest sources of supply, both for the United States and the rest of the free market countries, are Zaire and Zambia (see table 2-8). In the past 4 years, world supplies have been expanded and diversified; other countries such as New Caledonia, the Philippines, and Austrialia now make a greater contribution to world supply. This expansion was also induced by the cobalt price spike in the wake of the Katanga invasion of Zaire's mining belt in 1978. Zairian cobalt currently accounts for about 43 percent of U.S. imports, compared with 53 percent before the 1978 cobalt panic. Despite the considerable number of suppliers at present, Zaire and Zambia have

Table 2-7.—U.S. Consumption of Cobalt, 1978-82

Year	Apparent consumption[a] (short tons cobalt content)	Net import reliance[b] (percent)
1978	10,182	95
1979	9,403	94
1980	8,527	93
1981	6,266	92
1982	5,592	92

[a] Apparent consumption = U.S. primary and secondary (recycled) production and net import reliance.

[b] Net import reliance = (imports − exports + changes in government and industry stocks) ÷ apparent consumption.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries*, 1983 and 1984.

Table 2-8.—Sources of U.S. Cobalt Imports

Country	1979-82 (percent)	1982 (percent)
Zaire	37	39
Zambia	13	9
Canada	8	12
Belgium-Luxembourg[a]	8	5
Finland	7	6
Japan[a]	7	8
Norway[a]	7	7
Botswana	3	3
France[a]	3	3
Other	7	8

[a] Processes cobalt ore originating from other countries.

NOTE: Major world producers of primary cobalt and their contribution to world supplies in 1982 were: Zaire (45 percent); Zambia (13 percent); Australia (9 percent); Soviet Union (9 percent); and Canada (6 percent). See table 5-16 of ch. 5 for more detail, and for information on reserves.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook*, 1980, 1981, 1982, and 1983.

substantially the largest and richest cobalt ore deposits. Due to these reserves, these two countries promise to continue to dominate cobalt supply far into the next century.

The United States has sizable cobalt deposits, particularly at the Blackbird Mine in Idaho, the Madison Mine in Missouri, and Gasquet Mountain in California. Substantial cobalt is also associated with copper-nickel deposits in the Duluth Gabbro of Minnesota. But the world price of cobalt (except during the panic) has been significantly less than what is needed to make U.S. cobalt mining economically feasible without government assistance.

Manganese

The dominant critical use of manganese, a gray-white or silver metallic element, is in steelmaking which accounts for about 90 percent of domestic manganese consumption. The addition of manganese prevents steel from becoming brittle. Normally, iron and sulfur compounds in steel tend to form at grain boundaries and weaken the steel at high temperatures. When manganese is added, the sulfur bonds with it instead of the iron, forming a stable compound and avoiding weakness at grain boundaries. Manganese also has uses as an alloying element to impart strength and hardness to all grades of steel. For example, manganese-alloy steel is used for armored vehicles that withstand impacts.

Only 10 percent of U.S. manganese consumption goes into nonsteel applications. Manganese dioxide is used in batteries for its oxygen content, wherein the oxygen combines with hydrogen, which would otherwise slow the cell's action. Manganese dioxide is also used in making chemicals, in the leaching of uranium ores, and in the electrolytic production of zinc.

For these smaller uses, manganese has some substitutes. Although no satisfactory *material* replacements for manganese exist in iron and steel production (see ch. 6), there are *functional* substitutes for manganese in steelmaking: external desulfurization is reducing the manganese requirement for sulfur control and several other process modifications in steelmaking also reduce manganese requirement or improve manganese recovery.

Domestic consumption of manganese has declined slightly in recent years (table 2-9). The big drop in 1982 is due to the recession in the steel industry.

There is no domestic production of "manganese ore" (defined as ores containing more than 35 percent manganese). The United States relies on import sources for 99 percent of its supply, with the remaining 1 percent recovered from domestic production of manganiferous ores that contain less than 35 percent manganese.[19] Ferromanganese and silicomanganese—alloys used in steelmaking—are also highly imported.

The largest suppliers of manganese materials to the United States are Gabon and South Africa, as shown in table 2-10. The U.S.S.R. and South Africa have by far the largest manganese deposits in the world. However, Australia and Gabon are well-endowed with reserves which could last a century or more at

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[19] The iron and steel industry derives a significant quantity of manganese from iron ores charged to the blast furnace. This input accounts for approximately one-third of total consumption, but it is not included in manganese import statistics. The quantity of manganese contained in these iron ores has been declining. Based on George R. St. Pierre, et al., *Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an Alloying Element in Steels*, report prepared for the Office of Technology Assessment, 1983.

Table 2-9.—U.S. Consumption of Manganese, 1978-82

Year	Apparent consumption[a] (thousand short tons manganese content)	Net import reliance[b] (percent)
1978	1,363	97
1979	1,250	98
1980	1,029	98
1981	1,027	99
1982	672	99

[a] Apparent consumption = U.S. primary and secondary (recycled) production and net import reliance.
[b] Net import reliance = (imports - exports + changes in government and industry stocks) ÷ apparent consumption.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries*, 1983 and 1984.

Table 2-10.—Sources of U.S. Manganese Imports

Country	1979-82 (percent)	1982 (percent)
Manganese ore:		
South Africa	30	52
Gabon	27	21
Australia	22	17
Brazil	13	3
Mexico	4	1
Morocco	4	4
Other	—	2
Ferromanganese:		
South Africa	43	49
France[a]	26	21
Mexico	6	7
Brazil	3	6
Australia	2	1
Other[a]	20	16

[a] Processes manganese ore originating from other countries.

NOTE: Major world producers of primary manganese ores and their contribution to world supplies in 1982 were: Soviet Union (41 percent); South Africa (23 percent); Gabon (7 percent); China (7 percent); Brazil (6 percent); Australia (5 percent); Mexico (2 percent). See table 5-22 of ch. 5 for further details, and for information on reserves.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook*, 1980, 1981, 1982, and 1983.

the current rate of production, and other countries also have significant reserves—all of which perhaps implies that supply vulnerability for manganese is somewhat less than that for other materials in the first tier. Nonetheless, the only large manganese reserve in the Americas is in Brazil. All sources of U.S. manganese imports (except a small amount coming from Mexico) require long-distance transportation by sea, which adds an element of vulnerability to U.S. supply. The tonnages required by U.S. industry rule out any other method of transport. Unclaimed resources are the manganese nodules which are found in large areas of the ocean floor (see ch. 5).

Platinum Group Metals

Platinum group metals (PGMs) refer to six metals which have similar properties: platinum, palladium, rhodium, iridium, osmium, and ruthenium. They have the ability to catalyze many chemical reactions and withstand chemical attack, even at high temperatures. Their leading use in the United States is in automobile catalytic converters, which use small amounts of platinum, palladium, and rhodium in each car. At present, there is no satisfactory substitute for this use of platinum group metals. Other catalytic applications are in petroleum refining, to produce high-octane gasoline, and in chemical manufacture of acids (e.g., nitric acid for fertilizer) and other organic chemicals.

The great strength, high melting points, and resistance to corrosion and oxidation of PGMs make them the material choice for electrical contacts and relays in telephone systems. PGM alloys are also used as crucible materials (e.g., for the growth of single crystals of oxide compounds, used for semiconductor substrates), in glass fiber manufacture, in dental and medical applications, and in jewelry. Most uses of PGMs as catalysts and in electronics are highly important to U.S. industry.[20]

U.S. consumption of PGMs declined in the 1981-83 recession but is now recovering (table 2-11).

Table 2-11.—U.S. Consumption of Platinum Group Metals, 1978-82

Year	Apparent consumption[a] (thousand troy ounces)	Net import reliance[b] (percent)
1978	2,635	90
1979	2,995	89
1980	2,859	88
1981	2,411	84
1982	1,787	80

[a] Apparent consumption = U.S. primary and secondary (recycled) production and net import reliance.
[b] Net import reliance = (imports - exports + changes in government and industry stocks) ÷ apparent consumption.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries*, 1983 and 1984.

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[20] National Materials Advisory Board, *Supply and Use Patterns for the Platinum-Group Metals*, NMAB-359 (Washington, DC: National Academy of Sciences, 1980).

The United States is highly import-dependent (85 percent) for PGMs. There is a small amount of domestic production (less than 1 percent of apparent consumption). The remaining 15 percent of demand is supplied by purchased secondary materials. Actually, this figure understates the amount of PGM recycling. If consumption is defined to include the PGM catalysts which are owned by refiners and chemical manufacturers, sent out for "toll refining,"[21] and then reused, recycling accounts for about 40 percent of total consumption. Chapter 6 discusses further recycling possibilities.

The Stillwater Complex in Montana is the most significant known U.S. deposit of PGMs. Development of an underground mine has been proposed for this site, with the decision on whether to develop the property scheduled for mid-1985. Small amounts of PGMs were recovered from placer deposits at Goodnews Bay in Alaska as recently as 1975. Chapter 5 has more details regarding PGM mineral deposits.

The largest source of PGM supply for the United States is South Africa. As table 2-12 shows, the South African deposits of the Bushveld Igneous Complex dwarf those of the United States and Canada. In fact, the U.S. and Canadian reserves combined would satisfy U.S. demand at the current level for only about 10 years. The Soviet Union is presently the world's largest producer of PGMs; its reserves are substantial but only about one-fifth the size of South Africa's.

Table 2-12.—Sources of U.S. Platinum Group Metal Imports

Country	1979-82 (percent)	1982 (percent)
South Africa	56	48
U.S.S.R.	16	16
United Kingdom	11[a]	13
Other	17	23

[a] PGM production from the United Kingdom is from ores originating in South Africa and Canada and from secondary materials.

NOTE: Major world producers of PGM and their contribution to world supplies in 1982 were: Soviet Union (54 percent); South Africa (40 percent); and Canada (4 percent). See table 5-33 of ch. 5 for further details, and for information on reserves.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Commodity Summaries*, 1983 and 1984.

PGMs are mined in South Africa for their own sake, while in the Soviet Union and Canada they are coproducts or byproducts of nickel and copper. Thus, South Africa has the advantage of responding directly to the PGM market in making production decisions. Moreover, the combination of PGMs in the ores is more favorable in South Africa than anywhere else, with a greater proportion of higher value platinum in the mix.

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[21] The term "toll refining" denotes the recycling of metals for a fee in which ownership of the metals does not change hands.

A Perspective on Strategic Materials Selection

For many reasons, no list of strategic materials can be the last word. It cannot be exhaustive: the cutoff point at the end of the list is bound to be somewhat arbitrary, separating materials which are "more" strategic from those that are "less," rather than representing ones that "are" strategic as opposed to those that "are not." Nor can the list be final. Conditions change. Take copper, for example. In 1952, the Paley Commission selected copper as a "key commodity," for which world consumption and U.S. net imports were rapidly rising.[22] The commission projected that by 1975, the United States would be able to supply only about 60 percent of its copper needs through domestic mine production and recycling. Thus, copper, which had a number of important industrial uses, might have been considered at that time as a good candidate for a strategic materials list. In fact, domestic copper production rose so much over 25 years that net imports fell to about 10 percent of consumption in the 1970s, rather than to the projected 40 percent, and were well below the 35 percent of 1950.[23]

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[22] The President's Materials Policy Commission, *Resources for Freedom* (Washington, DC: U.S. Government Printing Office, 1952), vol. 2.

The position of copper may change again in the future. American mines were closing in large numbers in the recession year of 1982, with some industry officials predicting that the mines would never reopen because high wages and pollution control costs had made the American copper mining industry—the world's largest—uncompetitive with foreign producers. Even if this prediction proves true, copper's designation as a strategic material will depend on many factors, including the nature of its use, the availability of substitutes, and the number and character of foreign suppliers.

The continual development of new materials and uses also tends to make lists of strategic materials out of date. For example, natural rubber was a strategic material of great concern to the United States before World War II. But during the war, when imports of natural rubber from Southeast Asia were cut off, U.S. production of synthetic rubber expanded enormously. The displacement of natural rubber for most uses proved to be permanent.

Perhaps it is most useful to look at the strategic materials selected for careful analysis herein as *indicative* of a set of problems and possible solutions, not as fixed or exhaustive.

The brief discussion above—much amplified in chapters 3 and 4—indicate why cobalt, chromium, manganese, and PGMs are judged to be highly strategic materials. Because they meet all, or nearly all, of the criteria for critical uses and vulnerability of supply, they have been selected for detailed examination in this report. The essential functions of these materials, present and anticipated, potential substitutes, and technologies that can reduce dependence on uncertain supplies are discussed at length in the chapters that follow.

The second-tier materials, which share some strategic characteristics with those of the first tier, are described in appendix C. These materials, though judged to be less strategic than the first four, are still worthy of attention and study. As a practical matter, this report must confine its assessment to a manageable number of materials. The four first-tier materials are judged to be *most* strategic, and they present the problems of import vulnerability and possible solutions in the most striking way. Thus, the assessment here may serve as a useful model for studying other materials which, though judged less strategic, may be of some concern because of combined factors of vulnerability and criticality.

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[23] Data on production, reserves, and imports of minerals come from the Bureau of Mines, Department of the Interior.

CHAPTER 3

Critical Materials Consumption: Current Patterns and Trends

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CHAPTER 3

Critical Materials Consumption: Current Patterns and Trends

The metals that form the principal subject of this report—chromium, cobalt, manganese, and the platinum group—serve throughout the economy in applications that range from the essential, such as structural applications in high-performance aircraft, to the decorative, as in trim and jewelry. These metals are strategic because they are necessary in a number of essential industrial and defense applications and because the major sources of supply are considered to be vulnerable to disruption. This chapter identifies the major essential uses of these metals, describes the properties that make them irreplaceable at present, and discusses the trends in their use.

As discussed in chapter 2, the strategic nature of these materials is not static. In time, alternatives may be found to replace the metals in essential functions, or changing conditions may mean that the functions are no longer essential. It is also possible that changes in technology will cause these metals, or other materials, to increase in importance beyond their current status. Such changes are slow in coming, however, and are likely to take a number of years before they have a major effect.

Table 3-1 shows the distribution of consumption of the four metals over the major industrial sectors in the United States.

The transportation sector consists of the aviation, automotive, railroad, and maritime industries. These industries together account for 19 to 41 percent of the consumption of each of the four strategic metals.

The construction sector includes facilities for the production and processing of fuels; production of electricity; equipment for metallurgical, chemical, and food processing; and structural materials in buildings.

Examples of the uses of the strategic materials in the machinery sector are tools for metal cutting and forming, drill bits, ball and roller bearings, and other machinery components.

Important equipment in the electrical sector includes transformers, switchgear, motors, instruments, batteries, generators, cooling equipment, and household appliances. Major applications for strategic metals are in magnets, contacts and electrodes, shafts and bearings for rotating machinery, tubing and conduits, and decorative trim.

Refractory uses of strategic metals and minerals are those in which the materials must operate in an extremely high-temperature environment without chemical change or loss of desirable properties. An example is liners for boilers and furnaces. Materials for the production of ceramics and glasses are also in this category.

Chemical uses of chromium, cobalt, manganese, and platinum group metals are quite varied. They include dyes and pigments, preservatives, food additives, and catalysts for the production of other chemicals.

The listing in table 3-1 provides only a starting point for the analysis. Further detail on the uses of the metals is provided below.

Table 3-1.—Strategic Metal Consumption by Industrial Sector, 1980

	Chromium		Cobalt		Manganese		Platinum group	
Sector	1,000 tons	(Percent)	1,000 lb	(Percent)	1,000 tons	(Percent)	1,000 tr oz	(Percent)
Transportation	112	(19)	7015	(41)	215	(21)	731	(33)
Construction	123	(21)	0	(0)	375	(36)	171	(8)
Machinery	98	(17)	3081	(18)	165	(16)	0	(0)
Electrical	52	(9)	2530	(15)	67	(7)	526	(24)
Refractory	44	(7)	538	(3)	0	(0)	63	(3)
Chemical	87	(15)	3785	(22)	50	(5)	284	(13)
Other	71	(12)	190	(1)	157	(15)	431	(20)
Total	587	(100)	17,139	(100)	1,029	(100)	2,206	(100)

SOURCE: U.S. Bureau of Mines, Mineral Commodity Profiles, 1983.

Chromium

Chromium is the most versatile of the many alloying agents used in steel. It may be added to provide high-temperature strength, low-temperature toughness, hardness, corrosion resistance, or oxidation resistance. It is also a major constituent of nickel- and cobalt-based superalloys. Additionally, in the form of chromite, it lines crucibles for molten steel and is used in forms for ferrous castings. In the form of sodium dichromate, it is processed into a variety of chemicals.

Transportation Applications

Automotive Applications

The automotive industry is one of the largest consumers of chromium. Chromium consumption by the industry is on the order of 40,000 tons per year, mainly in the form of stainless steel. Of the 5.5 pounds of chromium contained in a typical 1980 car, the National Materials Advisory Board estimated that 2.5 pounds were used for functional purposes, including suspension, chassis, and engine components and the catalytic converter (table 3-2). Further reduction of chromium usage could be achieved through attention to the exhaust emission system, particularly through the use of stainless steel-clad carbon steel in place of the solid stainless steel now in use in the converter.

Parts of the automobile engine subject to high wear, high temperature, or corrosive environments are candidates for chromium-bearing alloys. Examples include exhaust valves, which may contain as much as 21 percent chromium, and camshafts, which range from 0.9 to 1.5 percent chromium. Engine components account for slightly less than 1 pound of chromium in an "average" automobile. Of this amount, only about one-third of a pound is essential, but there is little incentive to make the reductions under the present conditions of availability and price. Further, some of the reductions, such as the use of stainless steel containing 12 to 14

Table 3-2.—Chromium Usage in U.S.-Built Passenger Cars, 1980

	Total	Essential
Propulsion:		
Cylinder block, camshafts, valves	0.860	0.325
Cooling system, electrical system	0.016	0
Carburetors, air intake, exhaust	0.079	0
Catalytic converter	2.070	2.070
Drive train	0.155	0.067 (misc.)
Subtotal	3.180	2.462
Chassis:		
Wheel covers	0.971	0
Suspension	0.261	0
Brakes	0.032	0
Steering	0.013	0
Miscellaneous	0.093	0
Subtotal	1.389	0
Body:		
Windshield wipers	0.265	0
Seat belts	0.355	0
Roof and door moldings	0.032	0
Plating	0.041	0
Subtotal	0.903	0
Total	5.472	2.462

SOURCE: As projected by the National Materials Advisory Board in 1978.

percent chromium in place of the 21 percent chromium alloy now in use could not be made without additional testing to ensure that the material would behave as expected when in service.

The principal structural use of chromium alloys in automobiles is in the AISI 5160 steel used for springs in the suspension. A relatively new, but growing, use is ~~in the main~~ structural members of the chassis where high-strength, low-alloy steels that contain about 1 percent chromium are gaining acceptance.

In 1982, General Motors (GM) introduced a fiber composite leaf spring into the rear suspension of the Chevrolet Corvette. In 1983, similar springs were introduced into other lightweight cars in the GM line.

Unlike the case with engine parts, there is a strong incentive to reduce the use of conventional steels in the structural parts of cars. That incentive is weight reduction, which results in reduced power requirements and lower fuel consumption. However, the development of the high-strength, low-alloy (HSLA) steels has provided an alternative to other lightweight materials such as aluminum and fiber composites. These steels, which obtain their strength through the use of small additions of chromium, manganese, molybdenum, and other metals, combine high strength and low weight with conventional metal-forming techniques. The overall economics of HSLA steels have led, and are expected to continue to lead, to increasing use of these alloys in automobiles. Although these steels are not essential to the design of cars, once incorporated into a design, any replacement of materials—e.g., in response to a reduction in the supply of chromium—will be difficult to make.

Aviation

Aviation, with its demands for high strength, low weight, and oxidation- and corrosion-resistant materials with long fatigue lives and resistance to high temperature, is another major consumer of chromium. Chromium consumption by the aviation industry accounted for 3,250 short tons in 1978, of which approximately 80 percent was used in jet engines as a constituent of superalloys and of other heat-, corrosion-, and oxidation-resistant alloys. Chromium-containing steels are used in other high-temperature components of jet engines, where the exceptional heat resistance of superalloys is not required.

Superalloys, containing substantial amounts of chromium, nickel, and, in some cases, cobalt, have exceptional resistance to high temperatures. These alloys retain their strength at high temperature and stress, whereas alloy steels would fail owing to creep (a gradual deformation of a material when it is subjected to stress at high temperature) or to rapid corrosion by the hot exhaust gases of a jet engine. These materials are essential in the current designs of aircraft gas turbine engines as well as many land- and sea-based gas turbine engines.

The manufacture of superalloys accounts for a majority of the total domestic consumption of chromium metal. In 1981, consumption of metallic chromium in superalloys was 2,500 short tons or 64 percent of the total domestic consumption of chromium metal. Ferrochrome is also used in the production of superalloys, in 1981, 4,300 tons of chromium contained in ferrochrome were used in superalloy production.

Already, hundreds of superalloys are used in aircraft engines, with more being developed all the time. Some of these alloys are in widespread use, while others have become obsolete or have been superseded by newer alloys. Table 3-3 identifies some of the typical alloys used in the most severe applications in the jet engine. With regard to the metals under examination, the table shows a range of chromium (Cr) content, from a low of 8 percent to a high of almost 26 percent, and a range of cobalt (Co) content from zero to 56 percent.

Substitution of known alternative alloys is a simple method of reducing critical metal consumption in times of a shortage of raw materials. During the disturbances in Zaire in 1978-79, the cobalt-free alloy IN-718 was used as a direct substitute for Waspaloy (13.5 percent cobalt). The alloy IN-718 may be used in place

Table 3-3.—Typical Structural Alloys Used for Hot-Section Components of the Aircraft Gas Turbine Engine

Alloy	Composition (percent by weight)			
	Ni	Co	Cr	Fe
Combustor liner:				
Hastelloy X	48	1.5	22	18.5
HA-188	22	41	22	—
Turbine vane:				
MA-754	78	—	20	1
MAR-M200	60	10	9	—
MAR-M247	60	10	8	—
MAR-M509	10	55	23.5	—
X-40	10.5	56	25.5	—
IN-713	72.5	—	13.5	—
Rene-77	55	15	15	—
Turbine blade:				
Alloy 454	62.5	5	10	—
MAR-M200	60	10	9	—
MAR-M247	60	10	8	—
B-1900	65	10	8	—
Rene-80	60.5	9.5	14	—
IN-713LC	72.3	—	12	—
Rene-77	55	15	15	—
Turbine disc:				
IN-100	56	18.5	12.5	—
MERL-76	54.1	18.5	12.4	—
Astroloy	55.5	17	15	—
Waspaloy	58	13.5	19.5	—
Rene-95	61.3	9	14	—
IN-718	53	—	19	18
IN-901	45	—	12.5	34
A-286	25.5	—	15	55
Case:				
Waspaloy	58	13.5	19.5	—
IN-718	53	—	19	18
IN-901	45	—	12.5	34
A-286	25.5	—	15	55

SOURCE: Office of Technology Assessment

of other alloys, such as MAR-M200 (10 percent cobalt) in turbine vane and blade applications. Savings of chromium are more difficult to achieve through substitution than savings of cobalt. Chromium contents of most superalloys are in the range of 8 to 22 percent, and those lowest in chromium contain 10 percent cobalt. The substitution of IN-718 (19 percent chromium) for MAR-M200 (9 percent chromium) offset cobalt savings by increased chromium consumption.

A substitution of cobalt-free IN-713 for alloy X-40 (56 percent cobalt) in the turbine vanes of the JT-9 engine used for wide-body commercial aircraft also occurred as a result of the cobalt price increases that followed the Zairian disturbances. This substitution also resulted in a 47-percent savings in chromium consumption, although that was not the object of the substitution. Normally X-40, with its longer service life, would be the preferred alloy, but at the higher cost and uncertain supply of cobalt, the substitution was justified.

The potential to reduce critical metal consumption in the near term is limited. Chromium is an essential component of all superalloys, and most of the easy substitutions for cobalt have been identified as a result of the price increases that followed the Zairian disturbances. Opportunities for further substitutions are known (and will be discussed in ch. 7), but the time required to complete the qualification and certification process for use in aircraft engines precludes their use as a short-term response to shortages.

It is clear that chromium will remain essential in superalloys for the aircraft gas turbine engine. Predicting future material needs cannot be done with confidence because of inherent inaccuracies resulting from factors that vary from the general state of the national economy to advances in engine design and materials processing. However, some sense of future material requirements is obtained by evaluating alternative scenarios for the growth of the U.S. aviation industry. Thus, it is estimated that in 1995 the United States will consume for the production of superalloys 3,700 tons of chromium metal and 6,500 tons of chromium in low-carbon ferrochrome for an increase of 50 percent over 1981. Similar estimates for superalloy production for the year 2010, based on current technology and trends, are 6,800 tons of chromium metal and 11,600 tons of chromium in ferrochrome, an increase by a factor of 2.7 over 1981 demand.

Other Transportation Applications

Other uses of strategic metals in the transportation sector include heat-resistant chromium steels in gas turbines, in steam generators and turbines for railroad and maritime applications, and in stainless steel containers for transportation of dairy products and corrosive materials.

Construction Applications

Almost 20 percent of U.S. chromium consumption is accounted for in the construction sector, with the most essential applications being in the corrosive environments associated with oil and gas production and refining and the high-temperature environment of energy production facilities. Chemical processing facilities also constitute essential uses of chromium in the construction sector.

Energy Production Facilities for Fossil Fuels

The annual chromium requirements for the construction of energy-related facilities, including oil and gas wells, coal mines, electricity generating plants, and other energy facilities were estimated in a 1979 report to the Department of Commerce. Reported consumption of chromium in 1977 by the energy industry was 20,400 short tons. When taken with the scrap generated during processing and fabrication of energy-related equipment, this sector alone accounts for 3 to 5 percent of U.S. chromium consumption. Similar estimates were made for chromium usage in a 1978 study by the National Materials Advisory Board (NMAB). These estimates are reported in table 3-4.

In its 1978 study, the NMAB estimated that 90 percent of the chromium consumption of the energy sector should be considered essential. Of the consumption in 2000, approximately 60 percent will be for stainless steel, with another 25 percent being for alloy steels. The remainder will be used in a variety of applications, including superalloys, plating, and nonferrous alloys.

Table 3-4.—Estimated Requirements for Chromium for Energy-Related Facilities, 1977-2000 (thousand short tons)

	Department of Commerce	NMAB low	NMAB high
1977.........	20.4	—	—
1985.........	24.7	—	—
1990.........	27.3	—	—
2000.........	33.2	—	—
Average......	27.2	19.5	33.7

SOURCES: U.S. Department of Commerce, 1979. National Materials Advisory Board, 1978.

Chemical and Process Applications

Production facilities of the chemical and process industries, manufacturers of acids, organic compounds, alkalies, and other corrosive materials, are major consumers of chromium, principally in the form of stainless steel. These steels are used because they combine strength with exceptional resistance to corrosion and oxidation. They are also used in applications where it is essential to prevent contamination of products by the process equipment.

The bulk of chromium consumption in chemical and process applications is accounted for by a few popular alloys: the wrought alloys; AISI types 304, 316, and 430; and the cast alloys, ACI types CF-8, CF-8M, and CN-7M. All of these steels contain approximately 18 percent chromium. In many cases, it appears possible to develop substitute steels with chromium content as low as 12 to 14 percent, although users would have to accept a lower resistance to corrosion unless additions of molybdenum were made to counteract the effects of chromium reduction. This class of steel, however, is not currently available, and several years of effort will be required before such steel could be ready for widespread use. Even if such substitutions were made throughout the industry, however, no more than one-third of the chromium consumption in this sector would be saved. Substitution by surface-treated materials, including coated, clad, and plated steels, could also be used in some applications, but limitations of cost, abrasion resistance, and corrosion resistance at welds and other joints restrict the opportunities to use these materials in the chemical and process industries.

Machinery Applications

Machinery applications of chromium include tool steels, spring steels, and alloy steels for gears, shafts, and bearings. Chromium is used largely for its contribution to hardness and wear resistance. The chromium content ranges from as low as 0.5 percent in some steels used for gears and bearings to as high as 12 percent in some tool steels.

Opportunities for reduction of chromium consumption in machinery applications include the use of sintered carbides in place of tool steels and alternative alloys containing manganese and molybdenum for the manufacture of gears, shafts, and bearings. Barriers to the use of these substitutes are economic rather than technical; in particular the high cost of sintered carbides relative to tool steels suggests that this would be an unlikely area of substitution except in extreme emergency.

Chromite Refractories

Chromium, in the form of chromite, is used in refractory applications such as liners for steam generator fireboxes and ladles for molten steel because of its ability to provide thermal insulation, resist stresses resulting from sudden changes of temperature, and remain chemically inert in metallurgical applications. The chromite used in refractories differs from that used as a raw material for the production of ferrochrome because of its higher aluminum content. While the high aluminum content makes chromite undesirable for ferrochrome production, it improves the refractory characteristics. Chromite sand is also used in molds for ferrous castings.

Refractories account for about 7 percent of U.S. chromium demand. Current data are not available but perhaps as much as 19,000 tons of chromium were lost in spent, unrecycled refractory bricks in 1974; additional chromite is contained in accumulated refractory wastepiles around steel mills, copper smelters, and other refractory-using facilities.

Steelmaking continues to account for most use of chromite-containing refractories, although its consumption has declined precipitously since 1965. Phase-out of open hearth steelmaking with basic oxygen furnaces that use virtually no chromite refractories is the primary cause. This decline was moderated, and partially offset, in the early 1970s by using chromite-containing refractories in electric steelmaking furnaces and in argon-oxygen-decarburization (AOD) vessels for stainless steel production. However, since the mid-1970s, chromite refractories have been replaced rapidly by water-cooled panels in electric furnaces. In addition, dolomite, which is readily available domestically, now accounts for about two-thirds of the refractory material used in AOD vessels, according to the major U.S. producer.

Electrical and Chemical Uses

In the electrical sector, chromium is used in shafts, bearings, and other applications requiring wear resistance and in decorative applications. Requirements for chromium are similar to those of the machinery sector.

Chemical applications accounted for 15 percent of total U.S. chromium consumption in 1980, principally in pigments, metal treatments, and leather tanning. Based on data compiled in 1976, the National Materials Advisory Board estimated 40 percent of the chromium use in chemical applications to be essential.

Cobalt

In contrast to the breadth of applications for chromium, uses of cobalt are limited. This is due, in part, to the availability of alternative metals that provide similar properties at lower cost. The current uses of cobalt are, therefore, those in which substitutions are difficult to achieve. The principal uses of cobalt are in superalloys (for the beneficial properties cobalt imparts at high temperatures), magnets, cemented carbides, and catalysts in petroleum refineries. Other uses include tool and alloy steels, and salts, driers, and other chemicals.

In 1982, the NMAB surveyed the uses and made estimates as to the essential needs of cobalt, in comparison to actual consumption. The results of these estimates are reported in table 3-5. The overall estimate of the NMAB was that 50 percent of the cobalt now consumed is essential, with over 58 percent of the essential consumption being accounted for in superalloys and another 14 percent of the essential uses going into cemented carbides.

Transportation Applications

The aviation industry accounts for the majority of cobalt consumption in the transportation sector. As shown in table 3-3, cobalt is an important constituent in many alloys in the jet engine. Superalloys may contain anywhere from no cobalt to 65 percent cobalt. The selection of a particular alloy is based on a range of properties, including yield strength, creep resistance, oxidation resistance, formability, and cost.

The beneficial properties that cobalt can impart to superalloys and its availability at reasonable prices (until the market disruptions of 1978-80) led to the current level of use of cobalt. The F-100 engine, used in F-15 and F-16 aircrafts, contains approximately 150 pounds of cobalt. The JT9D commercial aircraft engine contains approximately 165 pounds.

New engines may be designed to use cobalt-free alloys. The new General Electric F101 and F404 engines use Inconel MA 754, a mechanically alloyed, cobalt-free alloy, for the turbine vanes.

Superalloys accounted for 6.3 million pounds or 41 percent of the 1980 reported domestic cobalt consumption. Under current trends, it is anticipated that 8.3 million pounds of cobalt will be used in the production of superalloys in 1995 (for all applications, not the aircraft engine alone), and 12.9 million pounds of cobalt will be required for these uses in 2010.

Cobalt use in other parts of the transportation sector is small. Applications include hardfacing alloys used on the surface of exhaust valves in automobile engines.

Machinery Applications

Cobalt use in the machinery sector includes drill and cutting bits made for high-speed and high-temperature applications, surface coatings for hardness and wear resistance, and high-strength steels for rocket motor casings, and dies and structural uses in large machinery. These applications are met primarily through the use of three materials: cemented carbides, tool steels, and maraging steels.

Cemented Carbides

Cutting tools used for machining of steel and cast iron, mining and drilling bits, small- and medium-sized dies, cutoff tools, and screw-machine tools, all of which require qualities of abrasion resistance, hardness, impact resistance, and heat resistance, depend on cemented carbides for their demanding properties. Cemented carbide tools may account for as much as 75 percent of the metal removed in domestic metal-cutting operations and for over 50

Table 3-5.—Uses of Cobalt, 1980 (thousands of pounds)

Category	Reported consumption	Essential consumption	Essential fraction
Superalloys	6,300	4,500	71%
Magnets	2,300	400	17
Cemented carbides	1,300	1,100	85
Hardfacing	600	300	50
Steel	400	200	50
Other metallurgical	400	200	50
Catalysts	1,700	100	6
Salts, driers, and other chemicals	2,200	200	41
Total	15,300	7,700	50%

SOURCE: National Materials Advisory Board, *Cobalt Conservation Through Technological Alternatives*, NMAB-406, p. 2.

percent of the cutting and crushing functions in mining, oil and gas drilling, and construction activities.

Cemented carbides are formed from a mixture of tungsten carbide powder, which provides the hardness and wear resistance, and cobalt powder, which acts as the cement that holds the carbide particles together. The cobalt, carbon, and tungsten produce a synergistic effect that allows relatively easy production by sintering (heating the powder shape) to the point where the surface of the cobalt powder melts, dissolving some of the tungsten carbide to form an exceptionally strong bond.

Materials other than cobalt, notably iron and nickel, with some chromium when needed for corrosion resistance, have been used with some success as substitutes for the cobalt binder, but only with some sacrifice in performance. Since the applications of cemented carbides are in uses essential to the economy, and since there are no satisfactory substitutes for either the carbide tools or for the cobalt used in the binder, the use of cobalt in this application must be considered to be critical to the United States.

Tool Steels

Tool steels are used in a variety of metal cutting and forming applications, but it is only in the high-speed, high-temperature applications that cobalt-containing tool steel is of particular importance. These steels are clased as M-type and T-type. Past consumption of cobalt in these classes of tool steels is summarized in table 3-6.

Table 3-6.—Cobalt Consumption in Tool Steels
(short tons)

	1979	1980	1981
Domestic production:			
M-Type	2,905	2,941	2,344
T-Type	639	552	479
Subtotal	3,544	3,493	2,820
Imports	815	559	1,042
Total	4,359	4,052	3,892
Approximate cobalt content (8% average)	349	324	311

SOURCE: Office of Technology Assessment, based on data in National Materials Advisory Board, *Cobalt Conservation Through Technological Alternatives*, NMAB 406, p. 107.

Cobalt-containing tool steels have been a target for substitution research, which has produced alternative alloys with little or no cobalt through the use of powder metallurgy. For example, a new alloy, CPM Rex 20, is a replacement for the high-speed tool steel M42, and CPM Rex 25 may replace alloy T15.

Cobalt-based, hardfacing alloys have been used as wear-resistant materials for over 60 years. Applications include cutters, knives, and surfaces of unlubricated bearings. Representative hardfacing alloys include Stellite 1, 6, 12, and 21, all from Cabot Co., which range from 53.5 percent to over 67 percent cobalt content. A substitute alloy containing less than 14 percent has reportedly been developed, but it is not yet in commercial use.

Maraging Steels

Maraging steels are high-strength alloys that may be heat-treated in large sections and thicknesses to increase their strength further. They run from a low of 7.5 percent to a high of 12 percent cobalt. The major maraging steels are designated as 18Ni200, 18Ni250, 18Ni300, and 18Ni350. The composition of these alloys are listed in table 3-7. The last three digits of the specification (200, 250, 300, and 350) refer to the strength level of the steel, i.e., the 18Ni250 has a yield strength of 260,000 psi. These steels are noted for their ultrahigh strength with high toughness. The steels were developed for aerospace applications, but they are now also used in structural applications. Maraging steels achieve full strength and toughness through simple aging treatment (3 hours at 900° F or 480° C). Hardening and strengthening do not depend on cooling rates, so properties can be developed uniformly in massive sections with almost no distortion. Exact figures on consumption of maraging steels are unavailable, but during the 1976-78 period, annual consumption was in the range of 1,000 to 2,000 tons per year of steel, requiring 180,000 to 360,000 pounds of cobalt. Of this consumption, only part is included in the machinery sector. The remainder is consumed in aviation applications and is included in the transportation sector.

Table 3-7.—Composition of Maraging Steels

	Ni	Co	Mo	Ti	Al	Zr	B
18Ni200	18.5%	5%	3.25%	0.2%	0.1%	0.01%	0.003%
18Ni250	18.5	7.5	4.8	0.4	0.1	0.01	0.003
18Ni300	18.5	9.0	4.8	0.6	0.1	0.01	0.003
18Ni350	18.5	12.0	4.8	1.4	0.1	0.01	0.003

Ni = nickel
Co = cobalt
Mo = molybdenum
Ti = titanium
Al = aluminum
Zr = zirconium
B = boron

SOURCE: National Materials Advisory Board, *Cobalt Conservation Through Technological Alternatives*, NMAB 406, p. 110.

Chemicals and Catalysts

Cobalt is an essential material in catalysts for the refining of petroleum and for the production of chemicals. In 1982, about 1.5 million pounds of cobalt (down slightly from 1.7 million pounds in 1980) were used in petroleum refining and chemical production, of which all but 426,000 pounds were recycled.

In refining, cobalt-molybdenum catalysts are used to remove sulfur and heavy metals from petroleum, with molybdenum being the more active of the two metals. Substituting nickel for cobalt has proved somewhat successful, but opportunities are limited because nickel-molybdenum catalysts operate at higher temperatures and pressures than do cobalt-molybdenum catalysts. Without modification of the process equipment, the use of nickel catalysts would result in a decline in the processing efficiency and production rate of the refinery. Even accepting this drawback, cobalt cannot be entirely substituted because some reactors were not designed to operate under the more severe conditions required by nickel-containing catalysts.

Over 97 percent of the approximately 225 domestic petroleum refineries use some form of catalytic process. Hydroprocesses, which upgrade the quality of crude oil, are increasing in importance with the greater use of lower quality feedstocks. There are five important processes which are grouped as hydroprocessing: hydrotreating, hydrorefining, hydrocracking, residual hydrosulferization, and hydrogenation of pyrolysis gasoline. All use substantial quantities of cobalt-bearing catalysts. The annual consumption of cobalt in the petroleum industry is 970,000 pounds. Some cobalt is recycled, but about 340,000 pounds of high-quality cobalt are required every year for replacement of spent catalysts, principally for hydroprocessing catalysts which are not recycled. Although processes exist for recovery of cobalt, molybdenum, and other metals from spent catalysts, the majority is disposed of in landfills and dead storage while a small amount is exported.

Approximately 565,000 pounds of cobalt were used in catalysts for the production of feedstock for polyvinyl chloride and of unsaturated polyesters in 1982. Of this amount, 479,000 pounds, or 89 percent, was recovered through recycling. Generally, the particular processes have been designed around the cobalt catalyst, so substitution of alternative catalysts is not feasible. Only through the use of alternative chemical processes would it be possible to use a different catalyst.

Electrical Applications

Cobalt is used in the electrical sector because of its magnetic properties. Cobalt-containing magnets have many applications in electric motors and generators and in acoustic equipment, although a significant share of the market was lost to ferrite magnets as a result of the cobalt price increases in 1979 and 1980.

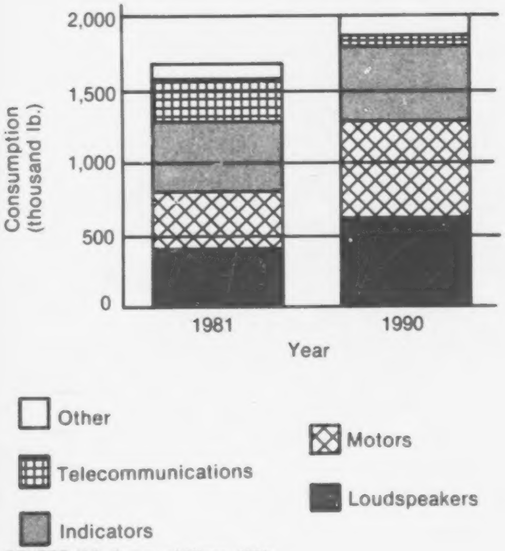
Cobalt is used in three principal types of magnets: the aluminum-nickel-cobalt (Alnico), iron-chrome-cobalt (Fe-Cr-Co), and rare earth-cobalt magnets. A fourth cobalt-containing magnet utilizes amorphous cobalt-base alloys that are rapidly cooled from a molten state to obtain a glassy, noncrystalline structure. The conventional Alnico and Fe-Cr-Co magnets account for 90 percent of the market for magnets, with the remainder being accounted for by the rare earth-cobalt magnets.

The price increases of the 1978-79 period initiated major efforts at substitution of noncobalt magnets (principally ceramic-hard ferrites) in magnetos and loudspeakers. These efforts were largely successful, to the point that even though the price of cobalt declined, the ferrite magnets retained control of their newly captured markets.

Most substitutions that could be made were made during the period of high cobalt prices, and further substitutions are unlikely, except in the event of an extremely severe shortage or major price increase.

The outlook for the future use of cobalt in magnets is for an extended period of relatively low growth, as shown in figure 3-1. The total growth for the 9-year period 1981-90 is estimated at 18 percent, or an annual rate of 1.9 percent. Most striking is the precipitous decline in cobalt magnets in the telecommunications area. This decline is due to increasing miniaturization, digital signaling, and large-scale integration.

Figure 3-1.—Current and Projected Cobalt Consumption in Magnets, 1981-90



SOURCE: U.S. Bureau of Mines, 1982.

The importance of cobalt in its present applications is indicated by Bureau of Mines' estimates that a threefold increase in cobalt price would only produce a 10-percent reduction in consumption, to about 1.8 million pounds in 1990. A much more drastic increase, a factor of 10, could cause a much more significant decrease, to approximately 400,000 pounds, which would be mostly in the loudspeaker and motor applications. This fraction (20 percent) of the normal consumption is viewed by the NMAB as the essential requirement for cobalt in magnetic applications.

Other Cobalt Applications

There are two principal uses of cobalt in the production of refractory and ceramic products. First, cobalt is used to prepare the surface of metals for binding by ceramic layers. In this application, cobalt, in the form of cobalt oxide, is added to the glasses that are applied to the steel base. Second, cobalt oxide is used as an intense blue pigment in ceramic products and as a decolorizer to offset the effects of iron and chromium in glass.

Organic salts of cobalt, which can be manufactured from any variety of cobalt metal or oxide, are used as driers in inks, varnishes, and oil-based paints. Inorganic salts and oxides are used in pigments, animal feed, and a variety of other applications, all of which consume relatively minor amounts of cobalt.

Manganese

Over 90 percent of manganese is consumed in the production of metals, mostly by the steel industry. The remainder is used within the chemical industry and the battery industry, and for various other uses. Table 3-8 shows the distribution of consumption among the metallurgical industries.

Manganese is used by the iron and steel industry in two forms: ore and ferroalloy. Ore is generally added during the ironmaking process, while ferroalloys may be added to the ladle after crude steel has been produced.

The function of manganese in the production of steel is to improve the high-temperature characteristics of steel by replacing harmful iron sulfide by the more benign manganese sulfide. When allowed to form, iron sulfide migrates to the boundaries between grains in the steel, where it remains liquid or extremely plastic after the rest of the steel has solidified. As the hot steel is rolled into useful forms, cracking results along grain boundaries, a characteristic known as "hot shortness." To control iron sulfide formation manganese is generally added at a ratio of 15 or 20 times the content of sulfur. In "resulfurized" steels, where sulfur is added to improve the machining properties, a minimum ratio of 7.5 parts manganese to 1 of sulfur may be acceptable.

Table 3-8.—U.S. Manganese Consumption,[a] 1980 (thousand short tons contained manganese)

	Ferromanganese	Manganese metal
Steel:		
Carbon steel	536	6
Full alloy steel	97	1
High-strength low-alloy steel	56	1
Stainless steel	13	2
Other steel	2	<1
Subtotal	704	10
Non-steel:		
Cast iron	21	<1
Nonferrous alloys	3	14
Miscellaneous	2	1
Subtotal	26	15
Total	730	25

[a] Data is based on information reported to the Bureau of Mines. Not all consumption is reported, so total reported consumption of manganese is lower than the apparent consumption reported in table 3-1.

SOURCE: George R. St. Pierre, et al., *Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an Alloying Element in Steels*, contractor report submitted to the Office of Technology Assessment, 1984, p. 97.

Manganese is also added to steel to improve the steel's strength, hardness, or toughness. Although other elements may be capable of imparting the same properties, manganese is often preferred because of its low cost and the past experience with manganese in similar uses.

One steel product with a high percentage of manganese as an alloying agent is the impact- and abrasion-resistant steel known as "hadfield" steel. This use accounts for approximately 70 percent of all high manganese steel. Total production of these steels is about 100,000 tons per year. The hadfield steels are noted for the property of work hardening where the strength of the material increases as it is used. Hadfield steels are extremely useful in applications where equipment is repeatedly subjected to high impact, such as earth-moving and excavation equipment.

Another steel with a high proportion of manganese is the 200 series of stainless steels. These steels were developed in the 1950s and 1960s in response to uncertainties over the availability of nickel. The addition of about 6 percent manganese to the 300 series of stainless steel allows the reduction of nickel content from 8 to 4 percent. The resulting steel has performance characteristics similar to the 300 series and enjoys a slight price advantage. However, compared with the widespread experience with the 300 series, satisfactory data on the performance of the 200 series in extended use is lacking. Moreover, producers have not promoted the 200 series. Thus, the use of the 200 series has been limited, and there is no expectation for any change in this pattern.

Manganese is also used in nonferrous applications. The largest of these is the 3000 series aluminums, which contain about 1.5 percent manganese. Estimated manganese consumption by the aluminum industry is between 10,000 and 15,000 tons per year, possibly growing to 20,000 by 1990. Manganese use in cast and wrought copper alloys is much less, on the order of 1,500 tons per year.

Manganese, in the form of manganese dioxide, is used in conventional carbon-zinc batteries. Manganese ore is used to produce potassium permanganate, drying agents for inks, paints, and varnishes, and as fuel additives. Manganese is also used to a small extent in fertilizers, animal feed, ceramics, and uranium processing.

Platinum Group Metals

The platinum group metals (PGMs) are noted for their stability in extreme environments. Resistant to high temperatures and to chemical attack, PGMs are used in furnaces for growing single crystals of oxide compounds, in the manufacture of glass fiber and high-quality optical glass, and in thermocouples and electrodes in electrical applications. PGMs are used as catalysts in the production of nitric acid, in the refining of petroleum, and in the treatment of exhaust gas from automobile engines. Contacts of both low- and high-voltage switches employ PGM alloys, as do integrated circuits and resistors. Other uses are in jewelry and in medical and dental applications.

The consumption of PGMs grew by a factor of 2.7 between 1950 and 1970. Consumption in the chemical industry more than doubled, petroleum refining grew to account for one-tenth of consumption, the electrical uses quadrupled, dental and medical uses doubled, and glassmaking became another important consumer. In that 20-year period, the only decline was in the jewelry and decorative sector. This was the single largest end user in 1950 accounting for 35 percent of consumption; in 1965 it accounted for only 5 percent.

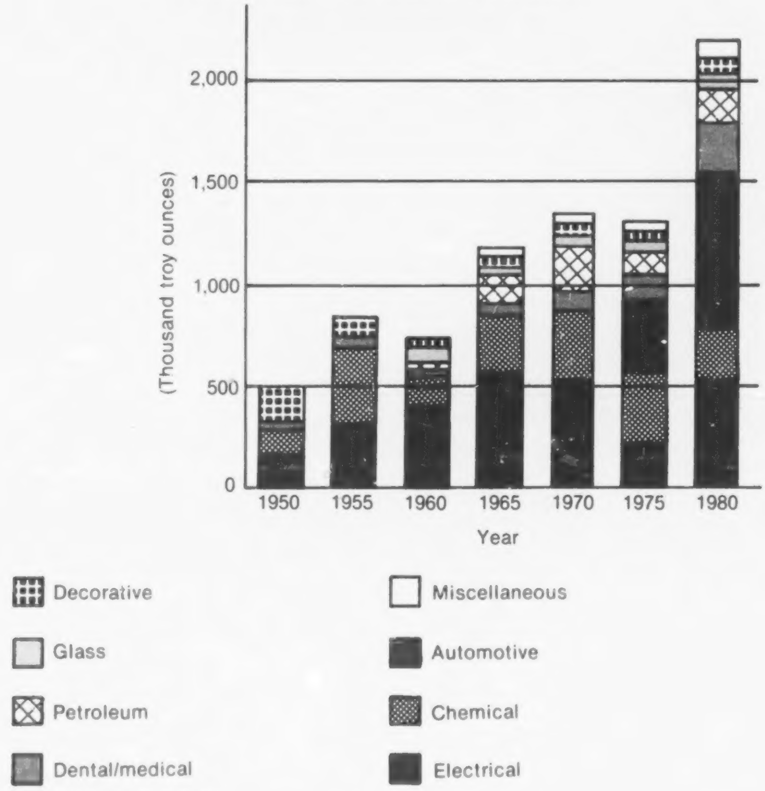
With the passage of the Clean Air Act in the 1970s (Public Law 91-604 and amendments), a new use for PGMs developed: the automobile catalytic converter. The catalytic converter was first used nationwide in 1975. Annual consumption of PGMs almost doubled within a decade. By 1980, the mix of end uses had shifted so that autos accounted for 33 percent of consumption, electrical, 24 percent; chemical, 13 percent; dental and medical, 12 percent; petroleum, 8 percent; and glass and jewelry, 3 percent each (see fig. 3-2).

Consumption patterns of PGMs differ among the metals. While the major use of platinum is in the automotive catalytic converter, the major uses of palladium are in the electrical and dental/medical sectors. The other metals are used largely in the chemical and electrical sectors.

Transportation Applications

The imposition of standards for automobile emissions resulted in the use of catalysts in automobiles, starting with the 1975 model year. As a result, the automotive industry quickly became the major consumer of platinum, the key element in the catalytic converter. In 1975, approximately 80 percent of all new cars were equipped with the converter. This converter, intended to promote the complete combustion of carbon monoxide and unburned hydrocarbons in the hot exhaust gas, averaged approximately 0.062 troy ounces of PGMs per car, of which about 70 percent was platinum and the remaining 30 percent was palladium. By 1983, virtually all new gasoline-powered cars and light trucks were equipped with catalytic converters. Tighter restrictions on the emissions, including oxides of nitrogen, lead to the development of a new three-way catalyst that uses more PGMs, including rhodium, an element not found in earlier converters. A typical con-

Figure 3-2.—Distribution of Platinum Group Metal Consumption by Applications



SOURCE: U.S. Bureau of Mines.

verter on a 1983 car contains, on the average, 0.079 troy ounces of PGMs, of which about 70 percent is platinum, 22 percent is palladium, and the remaining 8 percent is rhodium. The historical consumption of PGMs by the automotive industry is reported in table 3-9.

The future consumption of PGMs in the catalytic converter will be determined by two factors. First is the outlook for domestic production of cars and trucks. Forecasts of auto production are dependent on a number of factors, including the price of fuel, the general state of the economy, and the competitiveness of domestic producers with foreign producers. As a basis for estimating future PGM requirements, a range of forecasts, based on projections made for the Department of Energy, have been made and the baseline results are presented in figure 3-3.

Table 3-9.—Annual Consumption of Platinum Group Metals in Domestic Automotive Catalytic Converters

Year	Sales of gasoline cars and trucks (1,000s)	PGM (1,000s of troy ounces)
1975	9,346	443
1976	11,202	502
1978	11,979	491
1979	13,255	618
1980	10,431	704
1981	9,827	722
1982	9,512	685
1983	10,715	770

SOURCE: Sierra Research.

The second factor to affect critical metal consumption is the design of the catalytic converter itself. Despite predictions made at the converter's introduction, neither improvements in engine design nor research into alternative catalysts have resulted in the decline in impor-

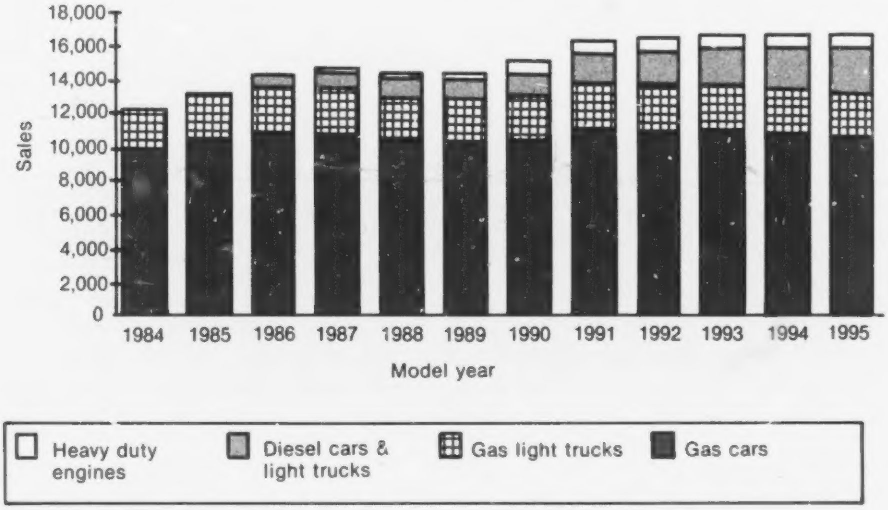


Figure 3-3.—Estimated Future Vehicle Sales in the United States

tance of the PGM-containing converter as the principal means of meeting air quality standards. This will probably continue to be the case for some time. While it appears possible to design an engine that could meet the air quality standards, it seems unlikely that any new design will soon be able to compete economically with the gasoline or diesel powerplant.

Based on the medium-growth projections for future sales of cars and trucks, and on the assumption that the catalytic converter will remain essentially unchanged, the projected annual consumption of PGMs in 1995 is estimated to be 1.4 million troy ounces. Consumption estimates for 1995 based on the high auto sales forecast are 1.7 million troy ounces of PGM, and the low forecast results in 1.1 million troy ounces of PGM. Estimated metal consumption for the period 1984-95 is shown in figure 3-4.

Construction Applications

Petroleum production accounts for approximately 9 percent of U.S. platinum consumption as measured by sales of new metal and refined scrap to industry. PGMs are used by the petroleum industry in two processes: reforming and hydrocracking. Unlike the case of cobalt catalysts, these metals are subject to tight monitoring and control, with the result that less than 10 percent of the annual consumption of these metals is lost in the petrochemical industry.

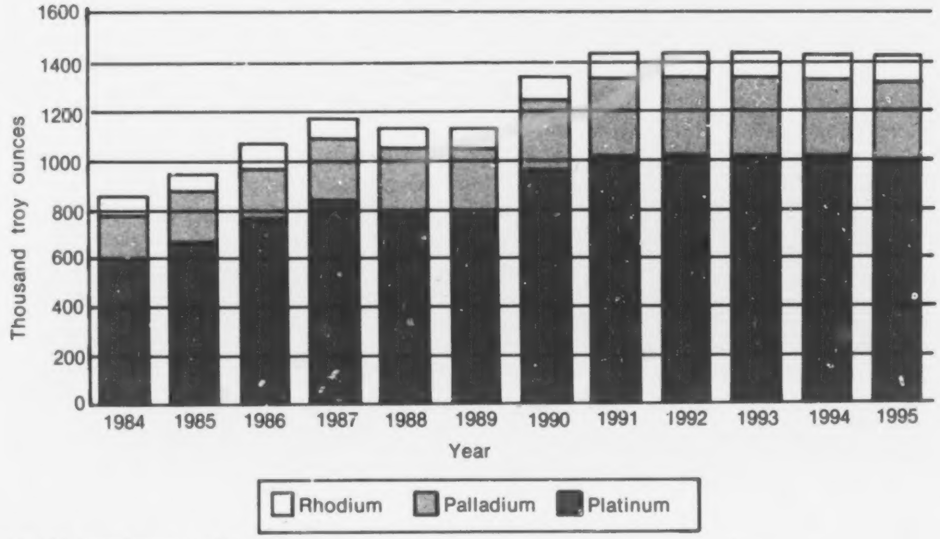
Chemical Applications

Chemical industry applications include the manufacture of nitric acid from ammonia. The PGMs contained in catalysts in these applications are largely recovered for reuse. New material is required for increases in processing capacity and to make up losses in recycling.

Electrical Applications

For many years, PGMs, particularly palladium, have been used in telephone switching systems, a use which is declining as a result of the rapid introduction of solid-state switches. In turn, the increased use of integrated circuits is resulting in increasing demand for PGMs. In integrated circuits, PGMs are used as contacts between the circuit itself and its outer package.

Figure 3-4.—Estmated PGM Requirements in Catalytic Converters for Domestic Automobile Production, 1984-95



SOURCE: Sierra Research, 1983.

Electrical Contacts

An essential property of electrical contacts in mechanical switching systems is low contact resistance, or low resistance to the flow of electricity through the surfaces of the contacts. This property is greatly influenced by the condition of the surfaces. Resistivity is increased either through the wear of the surfaces or through the creation of insulating films.

If contacts are to have high reliability and long life, they must be resistant to adhesive and abrasive wear. Adhesive wear occurs where the mating surfaces adhere to one another during sliding, resulting in the transfer of metal to the opposite contact, the edge of the contact area, or to debris. Adhesive wear is determined by the material's hardness and ductility and by the strength of the adhesive bonds which form between surfaces.

Resistance to corrosion is critical in electrical contacts. Most metals form insulating polymer or oxide films on their surfaces. Generally although not always, these films have lower conductivity than the surface metal. Even films only a few angstroms thick can cause substantial increases in contact resistance, so the selection of a surface material for contacts must consider the corrosive elements in the operating environment, the chemical products that may be formed by the contact metal, and the physical and electrical properties of those products.

Of the total consumption of PGMs in the electrical and electronics industries in 1981, approximately 50 percent went into the production of electrical contacts, mainly in devices for opening and closing circuits in telecommunications systems. Although gold contacts generally offer superior performance, cost considerations have resulted in the use of palladium and palladium-silver alloys. As a result of the increasing use of solid-state switching by the telecommunications industry, the consumption of palladium in this application will be declining for the rest of the century.

Ceramic Capacitors

Ceramic capacitors now constitute the major market for palladium in the electronic sector. The ceramic capacitor industry alone consumed approximately 500,000 troy ounces of palladium in 1983, which is expected to have doubled to 1 million troy ounces in 1984. Unit shipments of multilayer ceramic capacitors (MLCs), the largest and fastest growing class of ceramic capacitors, are expected to grow at nearly a 20-percent annual rate through the 1980s.

Multilayer ceramic capacitors are rapidly replacing the single-layer capacitor. MLCs are built of many thin layers of ceramic material, with electrodes made of gold, silver or PGM alloys separating each of the several thin layers. The electrodes exit on alternate ends of the capacitor, so the plates act in parallel, giving a larger effective area and a higher capacitance. The manufacturer controls the final capacitance of an MLC by varying the area, the thickness of the ceramic layers, the number of layers, and the dielectric constant of the ceramic. The end result is a sturdy, highly compact capacitor.

In creating MLC conductive layers, manufacturers use a metallic ink to print electrodes on a tape of ceramic material, which is then assembled into a capacitor prior to baking or firing into the finished component. The firing temperature necessary for the typical ceramic material (alkali-earth titanates)—about 1,350° C—is too high for silver alone to serve as the electrode material. Gold or platinum could be used but their high cost, several hundred dollars per troy ounce, leads manufacturers to use palladium or a palladium-silver alloy as the electrode material.

Driven by a need for lower costs, manufacturers have advanced MLC technology from the use of platinum electrodes in the early 1960s, to gold-platinum-palladium electrodes (which are still the most desirable, but most expensive, electrode material) in the late 1960s, to pure palladium in the 1970s, and most recently to silver-palladium. Even with this savings, however, the electrodes still account for 40 percent of the total material cost in the capacitor. In moving to the 70 percent silver alloy, manufacturers accepted some compromise in the properties of capacitors. The use of the high-silver electrodes, which have a lower melting point than the pure palladium electrodes they replace, requires a lower firing temperature to prevent oxidation of the silver during processing and to avoid reactions between the electrodes and the dielectric layers. The silver also tends to migrate into the ceramic during firing, which can lead to various electrolytic reactions, causing inconsistencies in performance and, possibly, failure of the capacitor.

With a higher melting point, nickel appears to have greater potential as a substitute material in the MLC electrode. Producers currently find nickel's properties difficult to control, but the Japanese are starting to use nickel in limited applications. The use of nickel requires expensive processing in an oxygen-free atmosphere, but the lower cost of nickel may provide incentive for further development.

A developing alternative to palladium electrodes is a lead alloy. In this process, known as the advanced Corning electrode, or ACE, the ceramic is printed with an ink made of a mixture of carbon-like powder and dielectric powder. During firing, the carbon material burns away, leaving the layers of ceramic separated by pillars of the dielectric powder. After firing, lead is injected into the voids left by the carbon powder. This process was introduced in 1983 by Corning (the sixth largest U.S. ceramic capacitor manufacturer), with encouraging results. If this process is able to produce consistently high-quality products, the lower cost of lead relative to palladium and silver will provide the driving force to encourage its widespread use.

Acceptance of new manufacturing technologies is often a long process. However, in the MLC industry, which is pressured by Japanese competition and by a growing demand for palladium that is certain to force prices upward, new processes may be accepted as quickly as they can be shown to provide the essential high reliability with reduced materials cost. Although the growing consumption of palladium in ceramic capacitors will continue for the next several years, technical advances spurred on by limited supplies of this metal are likely to provide lower cost alternatives that will eventually be accepted by the electronics industry, resulting in a slow, but long-term decline in palladium consumption in this sector.

Refractory Applications

PGMs are used as crucibles in the production of single crystals of certain oxide compounds that can only be manufactured at extremely high temperature. The high-temperature resistance, combined with the chemical stability, allows the production of crystals without danger of contamination by the crucible and tools used in the growth process.

PGMs are also used in the melting tanks, stirrers, and crucibles for melting high-quality glass and as dies and forming devices for glass fiber.

As with the catalytic uses of PGMs, the refractory and glass applications are largely recovered for reuse.

Other Applications

A variety of chemical compounds are used in cancer chemotherapy. In addition, PGMs are used in dental applications in dental crowns and bridges. These are all considered unrecoverable applications of PGMs.

Use of PGMs in jewelry has been relatively limited in the United States, but it is quite popular in Japan. Platinum alloys make good jewelry material, but they are easily replaced by gold.

Future Applications for Strategic Materials

Nonconventional Energy Systems

In recognition of the limited domestic reserves of petroleum and the limitations on the uses of coal in its natural form, the United States has devoted considerable effort to technological approaches to make efficient use of its energy resources and facilities. Some of this work has resulted in new energy systems that may have significant effect on U.S. needs for strategic materials. Several of the technologies that may have major requirements for strategic materials (particularly the PGMs) are discussed below.

Large-Scale Fuel Cell Stations

In order to make most efficient use of electrical generating capacity, a number of power storage systems have been examined. In one system now in use, electricity generated in off-peak hours moves water above a hydroelectric plant, allowing additional generation during peak hours without the need for expensive additional capacity. Another system being considered for the future is based on the fuel cell. The fuel cell is an electrochemical device that directly converts chemical energy into electric power. It can also reverse the process, converting electrical energy into chemical energy, storing it, and then converting it back into electricity when needed.

An example of current fuel cell technology is the phosphoric acid cell. In this system, hydrogen, which is obtained from methane or naphtha, is reacted with oxygen from the atmosphere to produce electricity and water. The phosphoric acid, which serves as the electrolyte in the cell, is kept at about 350° F. In order for the reaction to proceed, a platinum catalyst is necessary. Demonstration models of the fuel cell now require approximately 6.3 grams of platinum per kilowatt (kW) of power output. At a production level of 750 to 1,000 megawatts (MW) per year, as suggested by one developer as a target for 1995—in 2000, the annual platinum requirement of fuel cells could be as high as 6.3 metric tons (tonnes). This would be reduced to 1.9 tonnes per year if developers reach their target for reduced platinum loading of 1.9 grams per kW. The need for platinum may be eliminated if current research leads to development of alternative catalysts or alternative fuel cell designs that do not require platinum catalysts.

Synthetic Fuels

Currently, there is little synthetic fuel production from coal, oil shale, or biomass. Over the next 25 years, production of synfuels is expected to increase. Cobalt and PGMs will play a role in the development and growth of these energy sources.

Liquid and gaseous fuels from coal are expected to be the first large-scale synthetic fuels. Two processes for liquefaction of coal are known: direct and indirect. In the direct process, coal is hydrogenated to form a liquid in the presence of a catalyst, usually containing iron, although one process, the H-Coal process, uses a cobalt-containing catalyst. In any case, the liquid products obtained from coal and from oil shale will require substantial hydroprocessing of a type similar to that used with petroleum.

In the indirect process, coal is reacted with steam and oxygen to produce syngas, a mixture of carbon monoxide and hydrogen gas. The syngas is converted catalytically to methane (using a nickel catalyst) or to gasoline (using an iron or a cobalt-containing catalyst).

Critical Metals in Automobiles

The automobile of the future will certainly differ from those of today. With the large capital investment required to manufacture the millions of automobiles sold every year, it can be assumed that changes in design will not be radical, but even gradual changes may have significant effects on the consumption of strategic metals. One example is dual-fuel vehicles. These vehicles use a mixture of gasoline and methanol (from 3 percent up to 10 percent methanol). The methanol content requires a more corrosion-resistant material for the fuel tank, fuel line, and carburation system than is now used in automobiles. Stainless steel now offers the best performance characteristics for much of the fuel system when a gasoline/methanol mixture is used. However, auto manufacturers hope to develop alternative materials that will have lower raw material and fabrication costs.

Summary: Essential Uses of Strategic Metals

Attempts to predict future requirements for materials are fraught with difficulties, owing both to the uncertain growth of industrial and consumer needs and to unforeseen changes in manufacturing technology. Discussions of future essential requirements for specific materials are even more difficult since essentiality is not a simple yes-or-no characteristic. The need for a material in a particular application depends on the cost and performance of alternative materials and on the time available to replace the material, to redesign the component in which the material is used, or even to eliminate the need for the application altogether.

Despite the difficulties, however, it is necessary to **estimate** future materials requirements and to identify the applications in which chromium, cobalt, manganese, and PGMs are most essential. As a starting point, it is helpful to consider extrapolations of current materials requirements. The U.S. Bureau of Mines has made statistical projections of future materials requirements based on current patterns and trends; these are presented in table 3-10.

While these projections are useful as a starting point, there are a number of important modifications and clarifications that arise from a detailed study of the major uses of strategic metals. The major points are as follows:

- Chromium consumption for most applications, other than chemical and refractory uses, will require high-carbon ferrochrome. In the aviation industry, however, the requirement for low carbon content and high

Table 3-10.—U.S. Bureau of Mines Estimates of Probable Demand for Strategic Metals in the Year 2000

	Chromium		Cobalt		Manganese		Platinum group	
Sector	1,000 tons	(Percent)	1,000 lbs	(Percent)	1,000 tons	(Percent)	1,000 oz	(Percent)
Transportation	170	(22)	10,000	(32)	510	(36)	950	(28)
Construction	160	(20)	0	(0)	300	(21)	240	(7)
Machinery	120	(15)	5,000	(17)	220	(16)	0	(0)
Electrical	90	(12)	4,000	(13)	85	(6)	490	(15)
Refractory	30	(4)	(note 1)	(0)	0	(0)	220	(6)
Chemical	100	(13)	11,000	(35)	75	(5)	820	(24)
Other	110	(14)	1,000	(3)	230	(16)	670	(20)
Total	780	(100)	31,500	(100)	1,420	(100)	3,390	(100)

NOTE 1: Statistics on use of cobalt in glass and ceramics were combined with those on paint and chemical uses in 1983.

SOURCE: U.S. Bureau of Mines, Mineral Commodity Profiles, 1983.

purity will mean that the industry will need substantial amounts of low-carbon ferrochrome (6,500 tons of contained chromium in 1995) and chromium metal (3,700 tons in 1995).

- Requirements for PGMs in the electronics sector are likely to be considerably higher than projected by the Bureau of Mines owing to the rapid increase in palladium consumption in ceramic capacitors. Estimated consumption in 1983 of 500,000 troy ounces of palladium already exceed the Bureau of Mines' forecast of 300,000 troy ounces in 2000. Anticipated consumption of 1 million ounces in 1984 and a projected annual growth rate of 20 percent per annum indicate that estimates of PGM requirements for the electronic sector are low and in need of further study.
- Requirements for platinum, palladium, and rhodium in the automotive sector do not include PGMs contained in the catalytic converters of imported automobiles. Other factors, including the use of platinum-containing particulate traps will also result in higher consumption of PGMs. Estimated requirements for PGMs in catalytic converters in 1995, made by Sierra Research for OTA, are for 1.4 million troy ounces, almost 50 percent greater than the Bureau of Mines' forecast.
- Estimated consumption of cobalt, chromium, and PGMs do not distinguish between primary metal, produced directly from mined ore, and secondary metal obtained from prompt industrial and obsolete scrap.
- Estimates of future manganese requirements are based on the assumption that the ratio of manganese to iron used in steelmaking will decline by only 10 percent by the year 2000.

Although it is difficult to estimate the specific quantities of strategic metals that can be deemed to be essential, it is possible to identify the principal applications that are essential to the United States and that use chromium, cobalt, manganese, and PGMs to fulfill their functions. These applications, and their strategic materials requirements, are summarized below.

Superalloys

Chromium, in the form of both chromium metal and low-carbon ferrochromium, is an essential element in superalloys. In addition, cobalt is currently used in a number of superalloys, particularly in the applications of highest temperature and stress. To meet future requirements for superalloys in gas turbine engines, jet aircraft, and other applications, the chromium requirements for 1995 are estimated to be 3,700 tons of chromium metal, 6,500 tons of low-carbon ferrochrome, and 8.3 million pounds of cobalt. Similar estimates for the year 2010 are 6,800 tons of chromium metal, 12,000 tons of chromium in ferrochrome, and 13 million pounds of cobalt.

Stainless Steel for Construction

Stainless and other alloy steels are used in the energy and chemical process industries to provide resistance to high temperature, corrosion, and oxidation and to limit contamination of chemicals that could occur from the use of less resistant materials in tanks, piping, and process vessels. In 1979, the Department of Commerce estimated chromium requirements for the energy industry at 27,000 tons in 1990 and 33,000 tons in 2000. NMAB estimates were lower (see table 3-4). The bulk of the chromium will be used as high-carbon ferrochrome, but a small percentage of the applications will be in special alloys that require low-carbon ferrochrome or chromium metal.

Automobiles

In automotive applications, the catalytic converter accounts for about 85 percent of the essential uses of chromium and all of the uses of PGMs. The estimated essential requirements for chromium in automotive applications will be 15,000 short tons in 1990 and 16,000 short tons in 1995. Requirements for PGMs are 1.3 million troy ounces in 1990 and 1.4 million troy ounces in 1995. Estimates for both chromium and PGMs are for all automobiles sold in the United States. Direct U.S. requirements for chromium and platinum metal will be reduced by the degree of market penetration made by foreign automobiles.

Cemented Carbides

Cemented carbides are one of the most essential applications of cobalt. There are no acceptable alternatives to cobalt for binding the carbide particles together, so virtually all cobalt in this use is essential. Estimates for 1995 cobalt requirements in cemented carbides are about 1.3 million pounds, rising to about 2.1 million pounds in 2010.

Industrial Catalysts

The use of catalysts in the petroleum and chemical industries is expected to grow at a high rate, more than doubling by the year 2000. Although in some cases there are alternatives to the processes that utilize cobalt and PGM containing catalysts, once facilities are constructed there is little opportunity to substitute an alternative process that reduces cobalt or PGM demand unless large investments are made to modify plant designs.

Manganese in Steelmaking

Manganese is essential to the manufacture of steel. The amount that is essential to the United States depends on the essential needs for steel, the mix of steel products (i.e., carbon steel; alloy steel; high-strength, low-alloy steel; and stainless steels), the sulfur content of the raw steel, and the efficiency of the steelmaking process.

Palladium in Electronic Components

Over the next few years, the use of palladium alloys as electrodes in ceramic capacitors will cause palladium consumption in the electronic sector to increase to a level substantially greater than indicated by the Bureau of Mines' estimates. However, the development of new technologies, which will be spurred by the limited availability of palladium relative to the needs of the manufacturers of ceramic capacitors, will then cause a decline in the demand for palladium.

CHAPTER 4

Security of Supply

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CHAPTER 4

Security of Supply

Import dependence—i.e., the proportion of demand supplied by foreign sources—is not the same as import vulnerability. The stability and reliability of foreign sources of supply, plus their number and diversity, are major factors in gauging whether or not this Nation is vulnerable to disruptions in the supply of a given imported material.

The preponderance of U.S. minerals imports comes from reliable sources—allies and close neighbors. Canada is this country's leading provider of nonfuel minerals, accounting for one-third of the total value of U.S. minerals imports. Of the 34 minerals shown in chapter 2 (fig. 2-1), Canada is the largest supplier of 12, including iron, nickel, zinc, tungsten, selenium, cadmium, asbestos, and potash. Australia is by far the United States' biggest source of rutile ore for making titanium (one of the essential metals for airplane parts and engines) and is a significant supplier of alumina and cadmium. Mexico is a dominant or major supplier of a dozen minerals, including strontium, fluorspar, natural graphite, silver, cadmium, and zinc; and Brazil sells the United States large amounts of manganese. Venezuela is a major provider of rich iron ore.

For a few specific minerals, however, the United States is highly dependent on a limited number of sources that could prove unstable. It may fairly be said that vulnerability of supply for some of these materials has increased over the past 30 years. Suppliers that were once colonial dependencies of Western European countries and reliable hosts to international mining companies are now struggling new nations. Many of them are experiencing difficulties in running their own nationalized minerals industries, and some are quite vulnerable to civil disorder and local wars.

Supplies even from sources regarded as reliable can be interrupted. Such was the case in 1969, when a months-long strike of the International Nickel Co. in Ontario sent nickel prices soaring and users scrambling for supplies. In addition, the security of imports from a friendly trading partner like Australia may be called into question because the supply lines are so long. Nor is domestic production proof against interruption of supply. For example, molybdenum was in short supply, here and abroad, from 1974 to 1979, even though the United States is the world's largest producer and exporter of this mineral. The shortage came about because of a world depression in copper production, of which molybdenum is often a byproduct, and because the large new Henderson mine in Colorado was not yet in operation. Moreover, in 1979, after the Henderson mine was producing, a 9-month strike at Canada's Endako mine kept world production of molybdenum flat. That year, spot market prices shot up to triple the mining companies' contract price.

It should be noted that the decline of the American steel industry may be said to increase the vulnerability of the entire U.S. economy, and to make the Nation less self-sufficient in defense. This troubling problem goes to the heart of U.S. economic strength and international competitiveness, and it is receiving sustained attention from analysts and policymakers. However, it involves many issues that are outside the scope of this report. Readers interested in these issues are referred to a prior OTA assessment, *Technology and Steel Industry Competitiveness.*[1]

Altogether, security of minerals supply hinges on a broad variety of factors. One concern, very much to the fore in the early 1970s but less so now, is the depletion of world resources in the face of escalating demand. An impermanent but recurring difficulty for many minerals is boom-and-bust cycles, with surges of demand coming from the most volatile parts of the economy during the time when users of the minerals are experiencing tight supplies, shortages, and high prices. In the bust side of the cycle, minerals investments in everything from exploration to modernization may decline precipitously, and some mines and plants that are closed down may never reopen.

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[1] Office of Technology Assessment, *Technology and Steel Industry Competitiveness*, OTA-M-122 (Washington, DC: U.S. Government Printing Office, June 1980).

Recently, concerns about security of supply have centered around the possibility of a cartel gaining control of critically needed minerals, of a Soviet-inspired squeeze on minerals from central and southern Africa, or of unplanned, unpredictable civil disturbances or local wars.

Factors That Affect Security of Supply

Depletion of World Resources

The Earth's resources are, of course, finite. But the minerals that underpin industrial society seem to be in no immediate danger of "running out" in the physical sense, at least for the next 30 to 50 years. Technology has continually extended both reserves—the identified inventory that can be mined profitably under present economic and technical conditions—and the larger body of known or potential resources. Table 4-1 shows the changes in proven world reserves of 13 minerals over 30 years. Most of them increased by at least 100 percent, and several by more than tenfold, even while world demand shot upward, especially in Germany and Japan.

The reason for the continued growth in reserves of the world's minerals is that the means of discovering them, mining them, and processing them have steadily improved. For example, through technological advances, many lower quality ores are now just as usable as the richer ones were before them. An important instance is chromium, where the distinction between the metallurgical grade of chromite ore, with its higher chromium content, and the lower chemical grade has lost most of its significance just in the last 10 years. Thanks to a steelmaking advance (called the argon-oxygen-decarburization or AOD process), high-carbon ferrochromium (made with the chemical grade of chromite ore) can be used in place of low-carbon ferrochromium (made with the metallurgical grade) in the production of stainless steel.

Another point about physical depletion is that nonfuel minerals, unlike fuels, are generally not consumed with use. Many can be recycled. In some instances, recycling may not be economical because the mineral ingredients in finished products are widely scattered, degraded, or inconveniently combined with other materials. Yet recycling is already an important source of supply for many minerals and could become more so with advances in technology.

How long technology can extend the life of the Earth's resources is, of course, a serious question. Just because it has done so satisfactorily in the past is no guarantee that it will in the future, especially when world population is growing at a staggering pace and soaring demands for resources may follow. Minerals economists generally argue that depletion would make itself felt as a persistent long-term

Table 4-1.—World Reserves of Selected Materials, 1950 and 1981 (tonnes unless otherwise stated)

Material	1950	1981	1981/1950
Bauxite	1.4×10^9	2.2×10^{10}	16
Chromite[a]	1.0×10^8	3.4×10^9	34
Cobalt	7.9×10^5	3.1×10^6	4
Copper	1.0×10^8	5.1×10^8	5
Iron	1.9×10^{10}	2.7×10^{11}	14
Lead	4.0×10^7	1.7×10^8	4
Manganese	5.0×10^8	4.9×10^9	10
Molybdenum	4.0×10^6	9.8×10^6	2
Nickel	1.4×10^7	5.4×10^7	4
Platinum group[b]	2.5×10^7	1.2×10^9	48
Tin	6.0×10^6	1.0×10^7	2
Tungsten	2.4×10^6	2.9×10^6	1
Zinc	7.0×10^7	2.4×10^8	3

[a] Chromium ore.

[b] Troy ounces.

SOURCES: For all 1950 figures except platinum group, John E. Tilton, *The Future of Nonfuel Minerals* (Washington, DC: Brookings Institution, 1977), p. 10. For 1981 figures and 1950 figures for platinum group, U.S. Department of the Interiot, Bureau of Mines.

rise in materials costs rather than an abrupt physical running out of stocks.[2] This expectation may be too optimistic. According to one geophysical theory, most metals have a "mineralogical barrier" beyond which the energy needed to release them from the rocks in which they are bound leaps 100 to 1,000 times. The barrier may be reached for all "geochemically scarce" metals—which is to say, all but five—within a century.[3]

The Earth's crust contains just 12 "geochemically abundant" elements, which account for over 99 percent of the mass. Five of these elements are metals: aluminum, iron, magnesium, titanium, and manganese. A steadily increasing amount of energy will be needed to produce even these metals from progressively leaner ores. But for all the other metals, a mineralogical barrier may exist, usually at ore concentrations of about one-tenth to one-hundredth of 1 percent, past which the metal is no longer concentrated in an ore body. Instead, it is dispersed as atoms, isomorphically replacing atoms of the abundant elements in common rocks. Once the mineralogical barrier is reached, the energy needed to release the scarce metals will be so great, and the prices so high, that according to the theory, new supplies of these metals will no longer be produced. According to this theory, a "Second Iron Age" will begin when "it will be simply cheaper to substitute iron and aluminum and put up with penalties, such as lower efficiencies in machines, that we do not now countenance."[4]

Analysts of the "cornucopian" persuasion concede that minerals depletion is in fact occurring, but they do not regard the loss as crucial.[5] The ultimate raw material, they say, is energy. Assuming that world population stabilizes, decent standards of living can be sustained indefinitely "provided man finds an inexhaustible nonpolluting source of energy."[6] They envision a new "Age of Substitutability," in which society would be based largely on glass, plastic, wood, cement, and the "inexhaustible" minerals: iron, aluminum, and magnesium. Whether societies have the capacity and foresight to plan a smooth transition from the present age of fossil fuels and materials abundance to the Age of Substitutability is a harder question. But, from the cornucopian point of view, there are no technical bars in the way so long as energy is available.

Demand Surges

Temporary shortages and price spikes for materials in response to peaks of demand have sometimes been interpreted as signs of resource depletion. Two major studies of materials policy were started, in fact, at a time of demand surge and materials shortages, one in the early 1950s during the Korean war, and another in 1973-74, when all the world's industrial countries were riding a wave of prosperity together. In both cases, the shortages proved short-lived. With a downturn in business activity, minerals industries found themselves with excess capacity, as they typically do after a boom is over.

Copper is an example.[7] Like many minerals, it is used in construction, transportation, capital equipment, and consumer durables. all of which react in exaggerated form to the peaks and valleys of economic activity. In 1973 and early 1974, with the economies of the United States, Japan, and Western Europe on a simultaneous upswing, there were serious copper shortages, aggravated by attempts of industrial users to build up inventories for security of supply. Within 2 years, the situation reversed.

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[2] See, for example, Hans H. Landsberg and John E. Tilton, with Ruth B. Haas, "Nonfuel Minerals," in *Current Issues in Natural Resource Policy*, Paul R. Portney with Ruth B. Haas (eds.) (Baltimore: The Johns Hopkins University Press, 1982), pp. 83-84.

[3] For a succinct statement of the theory, see Brian J. Skinner, "A Second Iron Age Ahead?" *American Scientist*, May-June 1976, pp. 258-69.

[4] Ibid., p. 267.

[5] H. E. Goeller and Alvin M. Weinberg, "The Age of Substitutability," *Science*, Feb. 20, 1976, p. 688.

[6] Ibid., p. 688.

[7] Copper is not generally regarded as a strategic material today because the United States is a large producer, and supplies are currently more than ample. The copper industry does clearly illustrate the cyclical nature of minerals production, whether of strategic minerals or less critical ones. In general, throughout this chapter, minerals that may not be strategic are used for illustrative purposes.

Prices slumped. Copper mines and smelters in the United States, the world's largest producer, were shut down. As industry revived in 1976-77, copper followed. With the recession of 1982, copper once more hit bottom, with prices dropping 30 percent in 2 years and mines closing throughout the American West. At the end of 1982, all of Anaconda's[8] mines and smelters in Montana were closed down or scheduled for closing. The huge Phelps Dodge open pit mine in Morenci, AZ, was shut down for several months in 1982—the first such closing due to a business slump since the Great Depression.[9]

Instability in the minerals industries is an old story, but some forces in recent years may be making it worse. One detailed study of fluctuations of industrial production in the United States, Japan, and several European countries concluded that the ups and downs of business cycles are now more pronounced than they were in the 1950s and 1960s, and that they are also more synchronized among the world's industrialized nations.[10] Other recent evidence suggests that stocks of copper held by U.S. industry are smaller than they were 20 or 30 years ago, and are not being used to counter swings in the business cycle as they once were.[11] The same may be true of other minerals. Another possible factor: U.S. copper mines and smelters seem to have suffered more than a proportionate share of the loss in times of low world demand in recent years, because nationalized mines in some developing countries have been kept open to save jobs and precious foreign exchange even when prices did not cover the costs of production.

Related to the surges and drastic drops in demand that are typical of minerals industries is lagging investment in mines and processing facilities. Inadequate investment while prices are low and facilities idle sows the seeds of future shortages. To be sure, such shortages tend to correct themselves, because the high prices they bring induce the needed investment. But lead times for opening new mines, processing plants, and support facilities are from 2 to 7 years, and meanwhile, industries dependent on the minerals may suffer hardship and dislocations for several years.

Cartels

The success of the Organization of Petroleum Exporting Countries (OPEC) cartel convinced many people that producers of other raw materials—bauxite, chromium, copper, phosphates, and perhaps tungsten—would get together to seize control of their markets. So far, it has not happened. One of the classic conditions for monopoly control does exist for quite a few nonfuel minerals; that is, a limited number of suppliers. In addition, some minerals are essential for certain industries with, at least for the present, no very good substitutes. Often, these same minerals account for a very small share of total production costs. These two factors make for inelasticity of demand and favor the success of cartel control of production and prices, at least in the short run.

There are several reasons why these conditions have not been enough to create a mineral cartel like the oil cartel. As noted earlier, the total costs of U.S. nonfuel minerals imports, compared with oil imports, are small. Also, most nonfuel minerals are far less bulky than oil and therefore much easier to store. Minerals-using industries generally keep a stock on hand, and the U.S. Government (although not European or Japanese governments) has a 1- to 3-year reserve of many critical materials to meet national defense needs in an emergency.

Significantly, markets for most nonfuel minerals have been soft since mid-1974. And for many producer countries (e.g., Zaire, Zambia) minerals exports are the mainstay of the economy. Considering the state of the market, the existence of government and private stocks, the existence of substitutes for many materials, the potential for development of substitutes for others, and the threat of new, alternate suppliers to any cartel, these producers could not risk supply stoppages. Most importantly, producer countries as diverse in ideology and goals as Zimbabwe, South Africa, and the Soviet Union might find it difficult indeed to cooperate in an OPEC-like organization that sets production controls and prices.

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[8] Now owned by The Atlantic Richfield Co.

[9] "Arco Unit to End Copper Mining in Butte, Mont." *Wall Street Journal*, Jan. 10, 1983; Jay Mathews, "U.S. Copper Industry, Beset by High Costs, Low Prices, Losing Out to Foreign Producers," *Washington Post*, June 22, 1982.

[10] David Chien, "Business Cycles and Instability in Metal Markets," *Materials and Society* 5(3), 1981, pp. 257-265.

[11] Timothy J. Grubb, "Metal Inventories, Speculation, and Stability in the U.S. Copper Industry," *Materials and Society* 5(3), 1981, pp. 267-288.

Producers of copper and bauxite did take steps to restrict supply and raise prices in 1974 and 1975. The copper effort, undertaken by members of the International Council of Copper Exporting Countries (CIPEC) was a failure. The CIPEC agreement to reduce copper exports by 15 percent had no effect on prices. Copper exporters thus turned to urging price stabilization agreements, which require the consent of purchasing countries. These efforts, made through the United Nations Conference on Trade and Development, also failed.

More successful was Jamaica's imposition of sharply higher taxes on bauxite. U.S. aluminum producers tolerated the higher price resulting from the tax because they had no alternative supplier as convenient as nearby Jamaica, and the cost of bauxite is a small fraction of the cost of finished aluminum. Nonetheless, during the aluminum recession of 1974-76, Jamaican output of bauxite dropped 30 percent, while bauxite production expanded in Australia, Guinea, and Brazil, none of which had imposed high taxes.

Because producer countries in the developing world had little success in the 1970s in creating minerals cartels does not guarantee that cartels will never succeed. Arguing against success is the distinct lack of common goals among producing countries and the deterrence exerted by stockpiles and substitutes. Arguing for it, in the short run at least, is the fact that a few important minerals are produced in a very few countries. It is worth keeping in mind that most minerals cartels in the past have fallen apart because consumers conserved or found substitutes, other suppliers got into production, and cartel members were tempted to cheat, raising output or lowering prices in the attempt to maintain their own income or foreign exchange. OPEC itself has been under severe strain for several years as a result of these factors.

Another point to consider is that monopolistic control of the market for economic purposes does not necessarily imply shortages or price leaps. Monopolies are certainly not unknown in minerals history. Past examples include Canada's Inco, formerly preeminent in world nickel production, and the Union Miniere of Belgium for cobalt in the days before Zaire's independence. In these instances, monopoly control resulted in rather reliable levels of production and prices that remained stable, although prices probably were higher than they would have been under competitive conditions.

Political Embargoes and the Resource War

As fears of cartel control over nonfuel minerals have faded somewhat, a new fear has grown that the supply of critical materials may be choked off for political reasons. Governments, including that of the United States, restrict both imports and exports to serve political goals. From 1966 to the end of 1971, the United States cooperated with United Nations' sanctions against the former British colony of Rhodesia, refusing to buy Rhodesian chrome because the colony resisted greater participation by blacks in the government. The United States has also prohibited nickel and other imports from Cuba since the 1960s.

Now, some analysts believe that the Soviet Union is carrying out a grand, long-term strategy to gain control of both Mideastern oil and African minerals, and to threaten the West with the loss of these critical materials. They believe that the Soviet invasion of Afghanistan, Soviet influence and the presence of Cuban troops in Angola and other African nations, and the buildup of the Soviet navy are all pieces of the strategy.[12] In their view, "state dominance," rather than commercial ownership, of mineral resources in Third World countries gives the Soviet Union access to these minerals through political agreement, backed up by Soviet military power.[13] Figure 4-1 shows the mineral-rich part of Africa which has prompted the greatest concern about possible Soviet control of resources.

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[12] Some publications expressing this view are Council on Economics and National Security, *Strategic Minerals: A Resource Crisis* (Washington, DC: 1981); and World Affairs Council of Pittsburgh, *The Resource War in 3-D—Dependency, Diplomacy, Defense* (Pittsburgh: 1980).

A variation of the resource war argument is that the traditional Soviet self-sufficiency in minerals is crumbling, and that the Soviet Union plans to rely on political and military domination of Africa rather than on costly economic competition with Western nations to get the resources it needs. Proponents of this idea point to Soviet and Eastern bloc purchases, beginning in 1978, of chromium, cobalt, manganese, tantalum, titanium, and vanadium, together with halts or large cutbacks in exports of platinum, gold, and titanium.[14]

Other observers of this situation find the picture of a full-scale resource war unpersuasive.[15] While not discounting "the desire and ability of the Soviet Union to create mischief for the United States and its allies,"[16] they see little evidence so far that Soviet activities in Africa are part of a grand design to grab minerals for themselves and deny them to the West. If the Soviet Union wanted to mount a direct challenge to the West on resources, these observers say, it would be far more likely to choose the Mideast than southern Africa. The Mideast is nearby and has the oil that is the West's lifeblood.

The actual behavior of African nations with Marxist governments and strong ties to the Soviet Union so far has not resulted in efforts to disrupt minerals supply to the West. All of them maintain economic relations with the West. They are keenly aware of their need for income and foreign exchange from minerals exports. Angola, for example, even with its thousands of Cuban troops, protects Gulf Oil facilities and encourages further foreign investment. Likewise, Zimbabwe is trying to expand its minerals exports, and Mozambique has growing American investment. One contributor to a series of scholarly papers on the Soviet Union and the resource war, prepared for the School of Advanced International Studies of the Johns Hopkins University, said:

> The vocabulary of the resource war, when addressing Southern Africa, mentions possible Soviet desires; often it neglects to examine Soviet abilities to realize their desires . . . Today, despite sizable military aid for the region from Moscow, probably all of the states harbor a healthy distrust of Soviet tactics and methods . . . Along with Soviet economic and political failings, [the region's] growing dependency upon Western economic institutions should preclude southern African states from becoming Soviet clients.[17]

This analyst believes the danger from Soviet influence will be greatest if South Africa continues its support of insurgent groups in neighboring black African states, including non-Marxist Zambia as well as Angola and Mozambique. The danger is that, to repel the insurgents, these nations might become increasingly dependent on Soviet military aid and might then be forced into a client-state relationship.[18]

Several observers report that they see little evidence of rapidly increasing Soviet dependence on imports of strategic materials. They believe that the recent Soviet buying forays for some minerals and the cessation of the sale of

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[13] William Casey, Director, Central Intelligence Agency, Speech to U.S. Chamber of Commerce, Apr. 28, 1981, reprinted in *Congressional Record*, June 23, 1981, S6779.

[14] Daniel I. Fine, "Mineral Resource and Dependency Crisis: Soviet Union and United States" in World Affairs Council of Pittsburgh, *The Resource War in 3-D*, cited in note 12. For a more moderate view of increasing Soviet dependency on minerals imports, with no conclusions drawn as to the consequences for a "resource war," see Daniel S. Papp, "Soviet Non-Fuel Mineral Resources: Surplus or Scarcity?" paper prepared for the School of Advanced International Studies (SAIS), The Johns Hopkins University, May 1981.

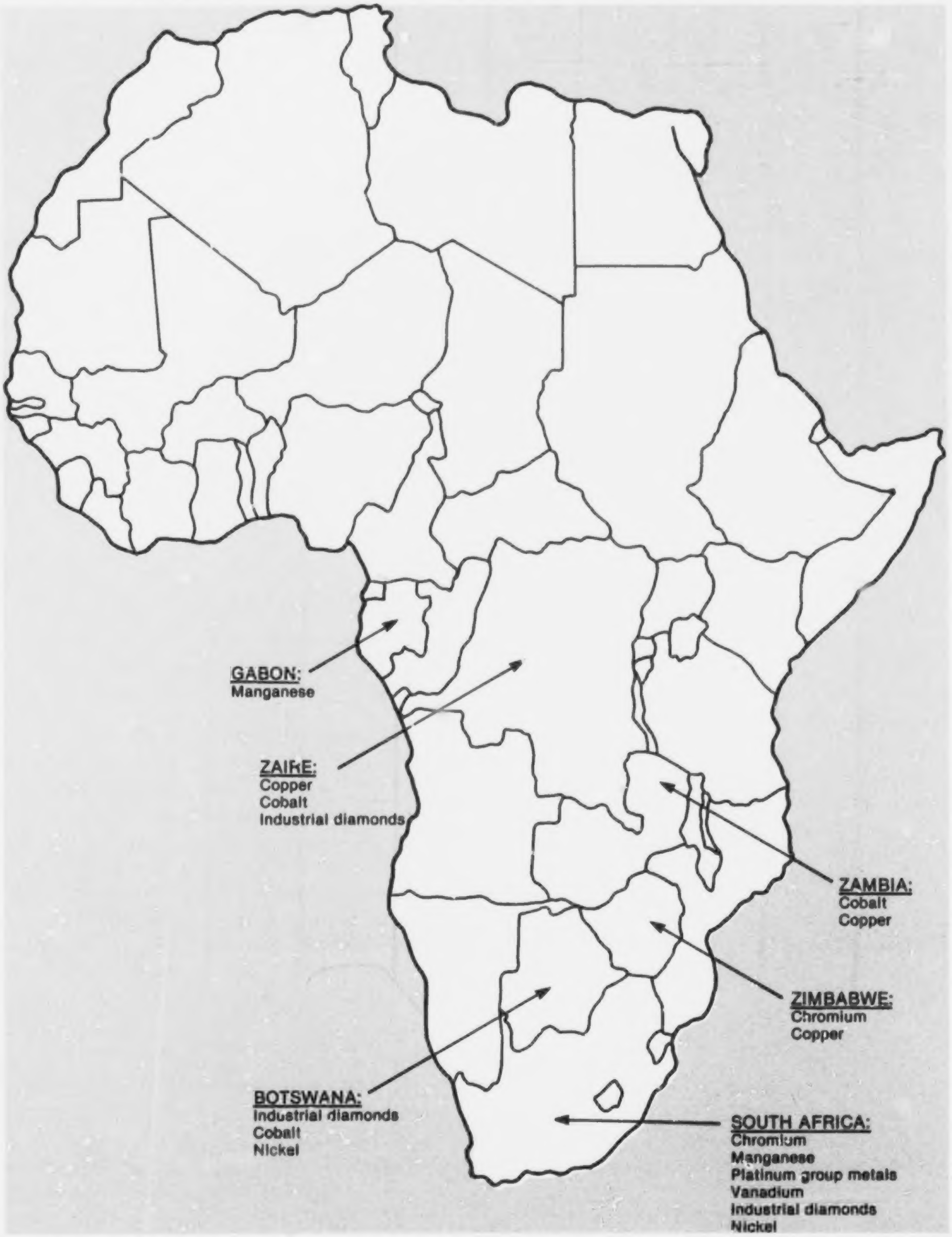
[15] See for example, Hans H. Landsberg, et al., "Nonfuel Minerals," cited in note 2; and Robert Legvold, "The Strategic Implications of the Soviet Union's Nonfuel Minerals Policy"; Herbert Howe, "The Soviet Union and Southern Africa: A Patron-Client Relationship?" Michael Moodie, "The Soviet Navy: A Weapon in the 'Resource War'?" Robert E. Osgood, "The Security Implications of Dependence on Foreign Nonfuel Minerals," papers prepared for the SAIS, cited in note 14.

[16] Hans H. Landsberg, "Minerals in the Eighties: Issues and Policies, An Exploratory Essay," paper prepared for the Oak Ridge National Laboratory, Oak Ridge, TN, 1982.

[17] Herbert Howe, "The Soviet Union and Southern Africa," cited in note 15, pp. 2, 5.

[18] Ibid., pp. 17-19.

Figure 4-1.—Selected Mineral Resources of Central and Southern Africa


GABON:
Manganese
ZAIRE:
Copper
Cobalt
Industrial diamonds
ZAMBIA:
Cobalt
Copper
ZIMBABWE:
Chromium
Copper
BOTSWANA:
Industrial diamonds
Cobalt
Nickel
SOUTH AFRICA:
Chromium
Manganese
Platinum group metals
Vanadium
Industrial diamonds
Nickel

SOURCE: Office of Technology Assessment, based on U.S. Department of the Interior, Bureau of Mines data.

others signify "the consequences of poor Soviet planning, shoddy maintenance of facilities, and low production efficiency," not an "emerging minerals shortage that could lend a common rationale to these actions."[19]

Indeed, as the quality of Soviet ores declines, and as new minerals exploration moves north and east into the forbidding Siberian environment, Soviet leaders may gradually abandon self-sufficiency as a top priority goal and may look to the outside world for cheaper, more convenient supplies of some minerals. But this does not necessarily imply that they will resort to strong-arm methods or a resource war to get those supplies.

One Soviet specialist asks: "Even were the Soviet Union shortly forced to import 5 to 10 percent of its lead, zinc, or titanium needs, what in that circumstance would begin to justify the risks of plundering Western sources of supply?"[20] Instead, he suggests, Soviet leaders wishing to buy a greater share of minerals abroad would use the conservative commercial approach they already use in foreign trade, possibly relying heavily on barter arrangements, or on development aid in which they are repaid in minerals.[21]

In sum, this school of thought holds that Soviet actions affecting the price and availability of African minerals is a matter of seizing opportunities rather than carrying out a strategic plan. They do agree, however, that the Soviet Union will go on trying to gain political power and influence in Africa by exploiting tribal conflicts, strong anticolonial feelings, and the opposition of black majorities to the rule of white minorities. Furthermore, they agree that mineral imports to this country and its allies from the richly endowed but troubled regions of central and southern Africa are definitely vulnerable.

Civil Disturbances, Local Wars, Internal Troubles

Civil strife, insurrections, difficulties of management, and breakdowns in mine production have, in the past, threatened the security of minerals supply from Africa. In many people's judgment, these are the kind of events most likely to cause interruptions of minerals imports in the foreseeable future.

The supply of Zairian cobalt, never actually cut off, has been threatened by insurrection and civil war in central and southern Africa. Angola's Benguela railway was the major route between central Africa's copper and cobalt mines and the rest of the world until the civil war shut it down in 1975. Zaire and Zambia had to scramble to find other exit routes for their minerals, including through South Africa, and are still relying on these less satisfactory routes. If the Angolan railway had shut down at a time of strong demand for minerals, the interruption might well have driven up prices and disrupted markets. In fact, the 1978 invasion of Zaire's Shaba province, with a brief occupation by the insurgents of the mines and processing facilities, had more serious consequences for the world cobalt market, as described later in this chapter.

In the future, the state of domestic peace and stability in central and southern African nations such as Zaire, Zambia, Zimbabwe, and Gabon, will strongly affect minerals production and export. Nor is South Africa exempt from the possibility of trouble. It is unknown how long South Africa can resist pressure for change and a possibly difficult transition to a new form of government with black participation. Even now, with white minority rule still firmly in place, the potential for disruption exists, as shown by the 1980 bombing of SASOL, South Africa's synthetic oil project.

A general war would, of course, be more profoundly disruptive than any of the circumstances described here. This report does not explicitly consider the contingency of general war. However, as a part of preparedness, the U.S. Government's stockpile goals are set with a 3-year conventional war in mind. Advanced technologies that reduce import vulnerability—the main focus of this report—are as valuable to the national interest in wartime as they are protective of U.S. economy and national defense in peace, but will not obviate the need to fulfill stockpile goals as a means to assure adequate supplies in the event of war.

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[19] Landsberg, "Minerals in the Eighties," cited in note 16. See also, William R. Severin, "Soviet Non-Fuel Minerals: Recent Trends and Prospects," prepared for the SAIS cited in note 14, and Legvold, cited in note 15.

[20] Legvold, cited in note 15, p. 17.

[21] Ibid., pp. 18-21

Materials Supply Interruptions Since World War II

In the years since World War II, supplies of several critical materials have actually been cut off quite abruptly on a few occasions. It is instructive to look at the reasons why the cutoffs occurred, how the economy and defense industries coped with shortages, and how the imbalance of supply and demand was eventually righted.

Soviet Embargo of Manganese and Chromium, 1949

When the Soviet Union blockaded Berlin in 1948, cutting the city's land links with the West, the United States clamped down on exports of industrial goods to the Soviet Union. Among the goods embargoed were machinery, tools, trucks, and scientific instruments. In retaliation, the Soviet Union cut off shipments to the United States of raw materials critically needed by U.S. industry, mainly manganese, and chromium.[22]

The loss could have been serious. The Soviets at that time were supplying one-third of U.S. manganese consumption and one-quarter of U.S. chromium. Soviet exports of manganese ore to the United States dropped from 427,229 tons in 1948 to 81,459 in 1949, and their chromium ore exports dropped from 393,966 tons to 107,131 tons. In both cases, much of the ore was shipped early in the year. Within a few months of the embargo, however, the United States had made up the loss with supplies from other countries.

For manganese, substitute supplies came mainly from the Gold Coast (now Ghana), India, and the Union of South Africa. These substitute supplies came from the expansion of already producing mines. Enough capacity of this kind was available so that U.S. imports of manganese in 1949 actually increased 23 percent over 1948, despite the embargo.

Actual use of manganese dropped in 1949, a recession year, but demand remained strong because industries added 45 percent to their inventories, probably as insurance against any possible shortages from the embargo. In fact, manganese prices rose about 15 percent in 1949 (compared with 8 percent the year before) despite the recession. At the same time, the recession probably softened any additional damage the embargo might have caused.

The U.S. Government, together with industry, swung into action to encourage the opening of more manganese mines outside the Soviet Union. India got steel from the United States to improve her rail system for transporting ore, Canada and the United States sent ore rail cars to South Africa, and the Gold Coast's railway and port equipment were improved. With the help of loans from U.S. banks and the World Bank, South Africa improved railways to mines and improved harbors for shipping ore. India got a World Bank loan to build an electric power project in the Damodar Valley, where manganese and other minerals were produced.[23]

The answer to the Soviet embargo of chromium was the same as for manganese: alternate suppliers. Turkey and the Philippines increased their chromium ore exports to the United States, and the Union of South Africa remained a major supplier. At the same time, because of the recession, U.S. chromium consumption fell by nearly one-quarter. Chromium imports dropped as well, prices fell, and industries added 20 percent to their inventories.

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[22] Contemporary accounts of the Soviet cutoff of manganese and chromium include Bureau of Mines' publications; *Business Week*, Sept. 10, 1949, p. 125; and *U.S. News and World Report*, Dec. 16, 1949, p. 26.

[23] The President's Materials Policy Commission, *Resources for Freedom* (Washington, DC: U.S. Government Printing Office, 1952), vol. 1, p. 74.

In the aftermath, the United States continued to diversify its suppliers of manganese and today buys none from the Soviet Union. The principal suppliers of manganese ore to the United States are South Africa, Gabon, Brazil, Australia, and Mexico. These countries are all large producers of manganese, and important suppliers in the world free market. While manganese ore producers are today quite diverse, the Soviet Union and South Africa together hold the great bulk of the world's reserves (known deposits, commercially minable) and of its identified (but subeconomic) resources.

As for chromium, U.S. imports from the Soviet Union resumed in the 1960s and for a time the Soviets were among the principal U.S. suppliers. That story is told next.

U.S. Embargo on Imports of Rhodesian Chromium, 1966-72

The British colony of Southern Rhodesia (now Zimbabwe) unilaterally declared its independence in November 1965, setting a course of continued white minority rule. The next year, the United Nations (U.N.) passed a resolution prohibiting member nations from buying any of a dozen export commodities from Rhodesia. On the embargoed list was chromium ore.

Before the ban, Rhodesia was one of the big four suppliers of chromium ore to the United States, second to South Africa and ahead of the Philippines and the Soviet Union.[24] Together, these four countries contributed five-sixths of chromium ore imported by the United States. Rhodesia and the Soviet Union each supplied about 35 percent of this country's imports of high-grade metallurgical ore, and South Africa supplied 17 percent. At that time, the metallurgical grade of chromium ore was essential for making stainless steel. (In the last decade, as mentioned above, technological advances have blurred the distinction between the metallurgical and chemical grades of chromium ore in stainless steel production.)

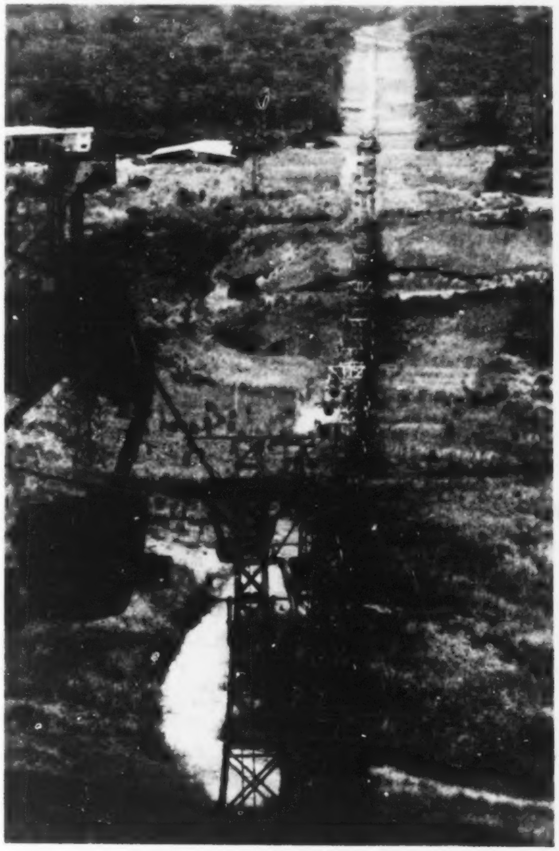

Photo credit: George C. Coakley, U.S. Bureau of Mines

An aerial tramway is one link of the transportation system that carries manganese ore from mines in Gabon to deepwater ports on the West Coast of Africa

When the United States complied with the U.N. ban on buying Rhodesian chromium, the Nation could have felt a real shock. Nothing so dramatic happened. First, the shock was cushioned by large sales from the U.S. Government stockpile. A long-range plan to rid the government stockpile of 1.9 million tons of "excess" metallurgical grade chromium ore had already been authorized before the mandatory ban on Rhodesian chromium took effect. In late 1966 and 1967, industry contracted to buy 666,000 tons of this stockpiled ore for future delivery. Deliveries of high-grade ore from the stockpile amounted to 66,237 tons in 1966 and 62,980 tons in 1967. These quantities compare with Rhodesian imports of 144,000 tons of metallurgical grade ore in 1966, before the embargo took effect. Large amounts of lower grade chromium ore were also available from the stockpile, but found no industry takers.

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[24] Contemporary accounts of the Rhodesian chromium embargo include Bureau of Mines' reports and *Business Week*, Nov. 27, 1971, p. 23.

Other factors also eased the effects of the ban on Rhodesian imports. Chromium-using industries had built up their stocks during 1966, when storm warnings from Rhodesia were apparent. Furthermore, deliveries of Rhodesian ore already purchased tailed off gradually over 1967.

At the same time, U.S. imports of metallurgical-grade chromium ore from the Soviet Union—and a year or two later from Turkey—began to increase. So did prices. For its exceptionally high-grade ore, the Soviet Union repeatedly raised prices, from around $32 per ton in 1966 to about $70 per ton in 1971. The price of Turkish high-grade ore rose comparably. Steelmakers throughout the industrialized world were competing for the more limited supplies of metallurgical-grade chromium ore available on the world market, and the suppliers took full advantage.

Nonetheless, it appeared that the ban on Rhodesian ore was being evaded. News accounts in 1971 reported that Rhodesian mines were going full blast and that chromium ore from Rhodesia was finding ways out despite the U.N. sanctions. France, Japan, and Switzerland, in particular, were accused of buying the Rhodesian high-grade ore under the guise of shipments from South Africa and Mozambique and of paying lower prices than for Russian and Turkish ore. There were suggestions, though no certain confirmation, that the Soviets were buying Rhodesian ore and reselling it at premium prices.

Members of Congress and the steel industry angrily protested that the embargo was forcing American steelmakers to pay higher prices for chromium than their European and Japanese competitors had to pay. Another theme in the protest was that the sanctions against Rhodesia had caused the United States to become dangerously dependent on Soviet chromium. Imports of Soviet metallurgical-grade ore had risen from 35 percent of total imports of that grade to 58 percent in 1970. (For total imports of chromium ore, of all grades, the Soviet share amounted to 29 percent in 1970, up from 16 percent before the embargo.)

The national defense argument was perhaps less telling than the economic one, because the U.S. Government still held large stockpiles of chromium ore, including the metallurgical grade. Moreover, a number of new suppliers had entered the market as chromium prices rose. Iran and Pakistan, as well as Turkey, became important alternate suppliers to the United States. Other countries raised production too. South Africa became the world's second largest chromium producer after the Soviet Union; and the Philippines, Turkey, Albania, India, Finland, and the Malagasy Republic (now Madagascar) all gained importance in the world market.

In November 1971, Congress passed legislation removing the President's authority to ban the import of strategic or critical materials from a non-Communist country. This ended U.S. participation in the U.N. sanction. During the next year, prices of Soviet and Turkish ore dropped 15 percent, rising only gradually with inflation over the next few years. The position of the Soviet Union as a chromium supplier to the United States rapidly declined, from 40 percent of chromium ore imports in 1972 (the peak year) to 12 percent in 1981. But the reasons were more complex than simply the end of sanctions against Rhodesia. Changes in the steelmaking industry were probably at least as important.

As technology advanced through adoption of the argon-oxygen-decarburization (AOD) process, making it possible to use the chemical grade of chromium ore for making stainless steel, the Soviet high-grade ores were no longer at a premium. By 1981, metallurgical-grade ores amounted to only 17 percent of chromium ore imports to the United States, compared to 50 percent or more 10 years earlier. Another change is that U.S. imports of chromium ore are giving way to imports of ferrochromium, just as ferromanganese is displacing manganese ore. South Africa led in changing its exports to the United States from chromium ore to ferrochromium alloys. Also, *all* of recent U.S. imports of chromium from Zimbabwe have been in the form of ferrochromium. As U.S. demand for raw chromium ore declined—particularly for the high-grade ore that was a Russian specialty—the Soviet Union no longer commanded preferential buying by American purchasers.

Today, South Africa is the United States' dominant supplier, contributing 55 to 60 percent of all U.S. chromium imports (including alloys as well as ore). The Soviet portion (of alloys plus ore) was 8 percent in 1981, with the Philippines supplying a like amount. Other substantial suppliers are Yugoslavia, Zimbabwe, Finland, Turkey, and Brazil.

Canadian Nickel Strike, 1969

Strikes in Canada's nickel mines in 1969 had a brief but jolting effect on nickel-using industries in the United States and Great Britain. Unlike the politically inspired embargoes described above, the 4-month strike at Canadian nickel mines caused actual shortages and acute price hikes. Yet military and essential civilian production were never interrupted in the United States, which was then at war in Vietnam. At the height of the shortage, scrap nickel was the main substitute for Canadian supplies, supplemented by larger nickel imports from Norway and the Soviet Union and ferronickel from New Caledonia (a French Territory in the Pacific) and Greece. A month after the strike was over, a large release of nickel from the government's stockpile helped refill the pipelines, while Canadian production geared up again. Within a year, prices and supplies were back to normal.[25]

The reasons for the acute effects of the cutoff of Canadian nickel supply were twofold: first, Canada's commanding position as a producer and exporter of nickel, especially to the United States; and second, tight supplies of nickel worldwide before the strike. In 1968 Canada supplied half the nickel for the non-Communist world, and was overwhelmingly the largest supplier of U.S. nickel imports, contributing over 90 percent. Imports were then 90 percent or more of U.S. nickel consumption. In addition, world demand for nickel had grown steadily from 1966 through 1969, while supplies lagged behind. The industrialized countries, increasingly prosperous, were demanding more nickel for stainless steel, alloys for jet engines and space hardware, long-life batteries, and dozens of uses requiring hard, strong, corrosion- and heat-resistant materials. Furthermore, the United States increased its nickel demands to satisfy military needs. In several countries, especially New Caledonia and Australia, mining companies were digging new mines and building new processing plants, but world production was only beginning to rise. There was practically no slack.

The big International Nickel Co. (Inco) mines in the Sudbury district of Ontario were struck in July 1969, and a month later strikes closed the mines of Canada's second largest producer, Falconbridge Nickel Mines Ltd. Immediately, prices on the dealer market (as opposed to producer prices charged by the mining companies) soared, rising from Inco's producer price of $1.03 per pound to $7 and even $9 per pound.

Nonessential industrial users without a ready substitute for nickel suffered real hardship. In particular, small electroplating companies using nickel for trim had to scramble for ma-

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[25] Contemporary accounts of the nickel shortage include Bureau of Mines' reports; *Business Week*, Oct. 25, 1969, pp. 42-44; Anthony F. W. Liversidge, "The Beguiling New Economics of Nickel," *Fortune*, Mar. 1970, pp. 100ff.

Photo credit: Inco, Ltd.

Entrance to the south mine at Copper Cliff in the Sudbury district, Ontario, Canada. Cobalt and platinum group metals are produced as byproducts of copper and nickel production

terial and pay the high prices or stop producing. Cobalt is an adequate substitute for nickel in electroplating, but usually sells at twice the price. During the shortage it was hard to find because most cobalt was sold by producers under contract to their regular customers.

Nickel-using industries that were able to use substitutes did so. For example, phosphor bronze was used in place of 12 percent nickel for electric powerplant hardware, and steelmakers offered chrome-manganese stainless steel instead of nickel-bearing stainless steel. The manganese stainless steel technology was already on the shelf. Steelmakers had developed it in response to fears of nickel shortages that arose in World War II and the Korean War; another motive was to have a substitute on hand in case nickel prices rose prohibitively. The shift to high-manganese stainless steel did not last past the nickel shortage, partly because nickel stainless steel has some superior properties (greater corrosion resistance) and partly because, at the time, the process of making high-manganese stainless steel was exacting and hard to control.[26]

The British, also 90 percent dependent on Canada for nickel, suffered shortages at least as severe as those in the United States. Looking back in 1982, spokesmen for the British Institute of Geological Sciences called the 1969 nickel shortage "perhaps the gravest metal crisis in the United Kingdom since the Second World War."[27] British steelmakers, like their American counterparts, offered customers a variety of steels in place of nickel steel.

Use of scrap nickel jumped 64 percent in the United States during 1969. Of the 23,300-ton drop from the previous year in Canadian imports, recycled nickel made up more than 9,000 tons. Everyone scrounged for scrap. Even new nickel products lying idle in inventories, such as pipes and fittings, were sometimes melted down for reuse. Some desperate electroplaters collected ferronickel scrap and swapped it for pure nickel, trading with foundries which had assured allocations from producers.[28]

As Canada's production slid nearly 20 percent from its 1968 level, several countries stepped up their nickel production, with New Caledonia, Australia, the Soviet Union, South Africa, and Rhodesia the leaders. The main substitute suppliers for the United States were Norway, which sold us 1,700 tons of nickel processed from ore obtained earlier from Canada, and the Soviet Union, which continued its expansion of nickel mining and increased exports to the United States by 700 tons. The Soviets also supplied additional nickel to hard-pressed Britain. The Soviets were reported to be the source of three-quarters of the high-priced dealer market nickel sold during the shortage.

The blow to the United States from the drop in Canadian imports was also softened by a large increase in ferronickel imports (from about 9,500 to 15,700 tons). Most of this came from Greece and New Caledonia. New Caledonia had a growing nickel minerals industry based on laterite ores.

Altogether, with additional imports from other countries and with the rapid rise in recycling, consumption of nickel in the United States dropped only 5 percent from 1960 to 1969, down from 173,700 tons to 165,400. However, it must be remembered that supplies had been tight since 1966. A better indication of the degree of shortage might be the U.S. consumption of primary and scrap nickel in 1970, which was 182,500 tons.

Throughout the shortage, defense industries continued to get nickel supplies. Three years before the strike, with nickel already in short supply, the government ordered the three principal U.S. nickel importers to set-aside 25 percent of their shipments for defense-related orders. The set-aside was continued after the strike, with the proviso that defense industries must use these supplies for current production, not for hoarding in inventories. Also, the government embargoed nickel exports. Most importantly, President Nixon directed the release of 10,000 tons of nickel from the government stockpile at the end of 1969. The strikes were over in November, but by this time the nickel supply pipeline was depleted. Without the stockpile release, shortages might have continued for several months.

By the end of January 1970, U.S. civilian as well as defense industries had all the nickel they needed. In fact, with rapidly rising production in several countries, nickel shortages disappeared entirely in 1970. Dealer market prices plunged from over $6 per pound at the first of the year to $1.33, the same as the producer price, at the end.

A lasting effect of the 4-year period of tight supplies in the late 1960s was to encourage more nickel production and greatly expand the number of suppliers. In the classic mode of the minerals industries, demand for nickel dropped off in the late 1970s, and some of the new capacity lay idle. Nearly half of Canada's mining capacity was unused in 1978, and New Caledonia, another big producer, had only about 60 percent of its mines in production.

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[26] To eliminate nickel completely in high-manganese stainless steel, nitrogen must be added as an alloying element. With the technology in use in 1969, it was difficult to add controlled amounts of nitrogen. Today, the argon-oxygen-decarburization (AOD) process is used almost universally in stainless steelmaking, and with this process it is easy to add controlled amounts of nitrogen.

[27] Institute of Geological Sciences, *Strategic Minerals*, memorandum submitted to the Parliament, House of Lords, Select Committee on the European Communities (Subcommittee F), Feb. 18, 1982.

[28] Liversidge, op. cit., p. 100.

The world's reserves and identified resources of nickel are not nearly so concentrated as those of chromium and manganese. Some of the Pacific islands (New Caledonia, parts of Indonesia) appear to be very well endowed, and there are also large deposits remaining in North America, the Soviet Union, Cuba, and Australia. Thus, the present diversity of producers can be expected to last for many years.

The Cobalt Panic, 1978-79

During the cobalt "shortage" of 1978-79, there was never any real interruption of supply. On the contrary, production in Zaire and Zambia—by far the largest cobalt producers for the world market—rose 43 percent during 1978 and 12 percent in 1979.[29] But the combination of rapidly rising world demand and fears of a supply cutoff, triggered by a rebel invasion of Zaire's mining country, set off a wave of buying that sent cobalt prices through the roof. Cobalt users turned to cheaper substitutes and recycling wherever they could, relieving some of the pressure. By 1982, with worldwide recession, cobalt prices plunged below the 1978 price.

Cobalt is a specialty metal, produced in small quantities (only about 27,650 tons worldwide in 1982),[30] but has a number of specialized uses for which it is highly suited, or even irreplaceable, at current levels of technology. Cobalt is critical for making certain high-strength, heat-resistant superalloys used in jet engines, and has highly desirable properties as a material for permanent magnets, wear-resistant tools, and catalysts for refining oil and making petrochemicals.

The threat of interruption of world cobalt supply surfaced in 1975 when the civil war in Angola shut down that country's Benguela railway. The Angolan railway had been the major artery for transporting copper, cobalt, and other minerals out of central Africa to the industrialized world. Central African cobalt is pivotal. In a typical year, Zaire accounts for 60 percent of cobalt production in the non-Communist world; Zambia, usually the second largest free world producer, contributes 10 to 15 percent. Thus, if cobalt cannot get out of Zaire and Zambia, world supply is in trouble. This situation of extreme world dependence on central African cobalt is aggravated by the fact that cobalt is a byproduct of mining for other higher volume minerals, mainly copper and nickel. In case of a supply cutoff in central Africa, it might be uneconomical in the short run, at least, for producers in other parts of the world to expand cobalt mining as such.

Because the Angolan railway shutdown of 1975 occurred during a world business recession, with demand low and industry stocks fairly high, Zaire and Zambia were able to find alternate routes for shipping metals from their mines without causing immediate distress. As of mid-1984, the Benguela railway was still closed because of guerrilla attacks (related to civil war in neighboring Angola and Namibia), and the makeshift exit routes were still being used. They are not very dependable. One alternate route to the port of Beira in Mozambique was closed when Mozambique shut its border to what was then white-ruled Rhodesia. (Now that Zimbabwe has a largely black, elected government, negotiations may reopen this route, although it too has been subjected to guerrilla attacks.) Meanwhile Zaire and Zambia ship their minerals out through the inadequate, backed-up port of Dar es Salaam in Tanzania, or take a long, expensive route through Zambia, Zimbabwe, and South Africa. Zaire uses its own western port of Matadi at the mouth of the Zaire River for some copper and cobalt shipments, but getting there requires arduous transshipment by rail and river, and the river is not always navigable. Figure 4-2 shows the routes and location of ports.

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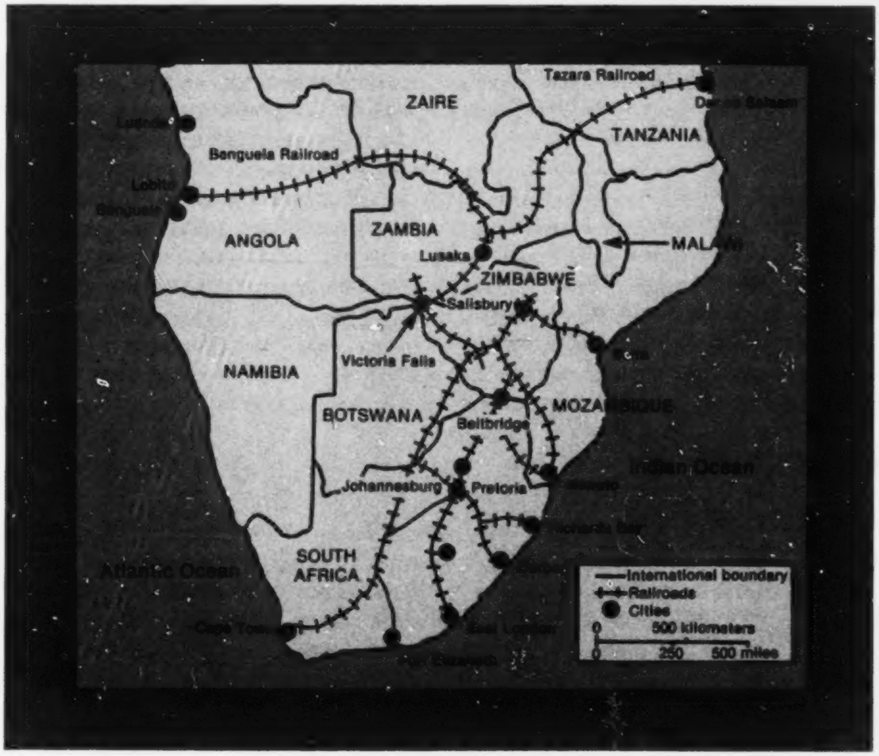
[29] Unless otherwise noted, data on cobalt production, consumption, uses, recycling, and prices in this section are drawn from Charles River Associates, Inc., *Effects of the 1978 Katangese Rebellion on the World Cobalt Market*, final report to the Office of Technology Assessment, December 1982. The data in the Charles River Associates' report are largely based on Bureau of Mines' figures, but with some adjustments. The account of events in Zaire and Zambia from 1975 on and of the cobalt panic of 1978 is also largely drawn from the Charles River Associates' report. Other sources were Bureau of Mines' publications, officials of the Amax Mining Co., and Patti S. Litman, "The Impact of Minerals Scarcity on Technological Innovation: Cobalt, A Case Study," an unpublished M.S. thesis presented to the Sever Institute of Technology, Washington University, St. Louis, MO, 1981.

[30] The figure cited is from Bureau of Mines' data.

With economic recovery in 1976 and 1977, U.S. and world demand for cobalt rose moderately, but not enough to cause real pressure on prices. In fact, Zaire was stockpiling cobalt hydroxide, an intermediate material produced in the processing of copper, to avoid building up unsalable inventories of cobalt. In 1977, a brief invasion of Zaire by insurgents based in neighboring Angola caused some concern for cobalt supply because Zaire's copper mines, from which cobalt is a byproduct, are in the southern Shaba province where the invasion took place. The rebels were emigres who had fled Zaire after losing a bid in the 1960s to create an independent state of Katanga in Shaba province. The invaders were quickly routed. The incident had no effect on cobalt production or prices.

In 1978, the situation was different. With world business activity on the upswing, and the market for new jet planes particularly strong, demand for cobalt began to heat up rapidly. Unable to expand production as fast as demand was climbing, Zaire announced in April 1978 an allocation scheme by which cus-

Figure 4-2.—Transportation Routes for Minerals in Central and Southern Africa


Tazara Railroad
ZAIRE
Dar es Salaam
Luanda
TANZANIA
Benguela Railroad
Lobito
Benguela
ZAMBIA
ANGOLA
Lusaka
MALA
ZIMBABWE
Salisbury
Victoria Falls
NAMIBIA
MOZAMBIQUE
BOTSWANA
Beitbridge
Indian Ocean
Johannesburg
Pretoria
SOUTH AFRICA
Atlantic Ocean
International boundary
Railroads
Cities
0
500 kilometers
0
250
500 miles

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Perspective: Zimbabwe*, 1981.

tomers would be limited to 70 percent of their purchases of the previous year.

Aggravating the tight world supply was a recent turnabout in U.S. policy for stockpiling cobalt. For 8 years, until 1976, the U.S. Government sold 6 million to 9 million pounds of cobalt each year from its strategic stockpile because holdings in the stockpile were far above what was then the official goal of 11 million pounds. During the years of the stockpile sales, these sales amounted to as much as one-half of U.S. cobalt consumption and 10 percent of consumption in the non-Communist world.

In 1976, after the Angola civil war cut the Benguelan railway, U.S. stockpile sales of cobalt came to a halt. With cobalt holdings then down to about 40 million pounds, the government set a new stockpile goal of 85 million pounds. Overnight, the United States went from being a major supplier of the world's cobalt to a potential major purchaser. Zaire, Zambia, and other cobalt-producing countries were unprepared for the change and had not geared up to higher production levels. But it was not until demand suddenly boomed in 1978 that the loss of U.S. stockpile sales began to pinch.

Shortly after Zaire announced its allocation scheme, insurgents from Angola reinvaded Shaba province. This time they succeeded in taking the mining headquarters town of Kolwezi, but after 2 weeks they were once again driven out. The only damage done to mining facilities was the flooding of one mine. But the publicity surrounding the invasion, the reported killing of 130 foreign workers, and the subsequent flight of several hundred skilled mineworkers and professionals raised the alarm about continued availability of cobalt. Around the world, industries tried to stock up, buying all the cobalt they could find.

Prices skyrocketed from $6.85 per pound (the producer price) in February to $47.50 per pound (dealer market spot price) in October. The producer price reached $25 per pound in early 1979. With this kind of demand and at these prices, Zambia airlifted its cobalt out, and Zaire also sent some out by air.

The typically slow response by the minerals industries to a surge in demand was aggravated in the case of cobalt because it is usually a byproduct. Nonetheless, producers responded to the cobalt price spike, as shown in table 4-2. Zaire raised output by producing from its stockpiles of cobalt hydroxide. Zambia opened a new refinery that was already under construction, improved cobalt yields, and pushed ahead with plans for new mines and refineries. Zaire and Zambia accounted for most of the added cobalt production in 1978 and 1979, but small increases occurred elsewhere. Two Canadian nickel companies added capacity to their cobalt refineries, and others made plans to recover cobalt from nickel slag. Recently opened nickel-cobalt mines in Australia and the Philippines raised their output as they solved technical problems and responded to demand.

The more remarkable response to high prices and tight supplies came from the industries that consume cobalt. A switch to substitutes or recycled materials swept some industries. By 1980, use of cobalt in the United States was estimated to be 19 percent below what it would have been without the price rise.[31] Demand for cobalt continued to drop in 1981, partly because of the weak economy and high interest rates. Consumption in 1981 was 11.7 million pounds—41 percent below the 1978 high of 20 million pounds. According to another informed estimate, 1981 consumption would probably have been 13 million to 15 million pounds if there had never been a "shortage."[32] Figure 4-3 depicts this estimate of the effect of the price rise in U.S. cobalt demand.

Where effective substitutes were ready on the shelf, the decline in cobalt use was steep. As table 4-3 shows, cobalt use in permanent magnets dropped by one-half in 3 years. Probably four-fifths of this reduction was due to the price spike.[33] Before the shortage, permanent mag-

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[31] Congressional Budget Office, *Cobalt: Policy Options for a Strategic Mineral* (Washington, DC: U.S. Government Printing Office, 1982), p. x.

[32] Charles River Associates, Inc., op. cit., p.1-6.

[33] Ibid., p. 3-12.

Table 4-2.—Mine Production of Cobalt in the Non-Communist World (tonnes)

	Australia	Botswana	Canada	Finland	Morocco	New Caledonia	Philippines	Zaire	Zambia	Zimbabwe	Total
1972	NA	—	1,520	1,270	1,602	NA	41	13,112	3,345	—	24,835
1973	NA	6	1,517	1,270	1,422	NA	41	15,052	4,300	—	29,418
1974	NA	33	1,564	1,270	1,627	NA	30	17,632	2,379	—	30,885
1975	NA	81	1,354	1,402	1,961	NA	117	13,638	1,843	—	20,396
1976	544	132	1,356	1,278	934	82	492	10,686	2,175	—	17,679
1977	1,000	163	1,485	1,227	1,015	109	1,084	10,215	1,704	—	18,002
1978	1,350	261	1,234	1,212	1,134	150	1,191	13,299	3,741	18	23,590
1979	1,500	294	1,640	1,065	961	210	1,370	14,996	4,280	210	26,526
1980	1,600	226	1,603	1,035	838	180	1,331	15,500	4,400	120	26,833
1981[e]	1,600	250	2,270	1,035	752	140	1,090	15,500	4,500	80	27,217

NOTES: Data reported for Australia and New Caledonia in 1975 are inconsistent with data for later years, so are not presented here.
Data for South Africa are not available.

SOURCE: Charles River Associates, Inc., *Effects of the 1978 Katangese Rebellion on the World Cobalt Market*, report prepared for the Office of Technology Assessment, December 1982.

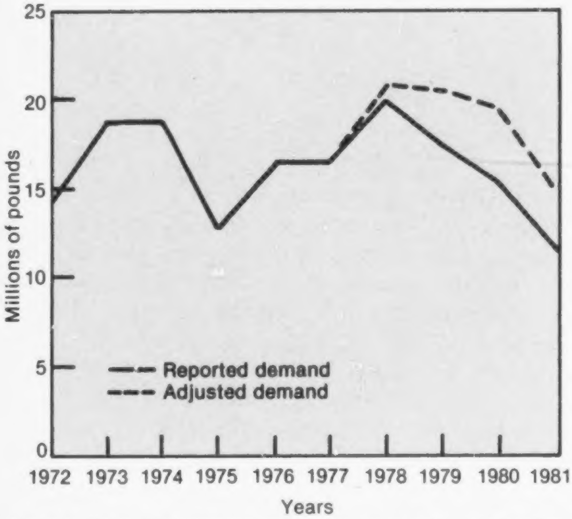
Table 4-3.—U.S. Consumption of Cobalt by Use (million pounds)

Year	Superalloys	Magnets	Cutting and wear-resistance	Welding and hardfacing	Tool steels	Other metallurgical	Catalysts	Salts and driers	Other	Total
1970	2.32	2.37	1.40	0.18	0.53	1.78	0.40	2.62	0.36	13.37
1971	1.98	2.28	1.23	0.25	0.32	1.25	0.47	2.74	0.44	12.50
1972	3.01	3.44	1.27	0.20	0.36	1.59	0.70	2.69	0.54	14.13
1973	3.28	4.30	2.51	0.39	0.52	1.85	1.15	3.57	0.64	18.74
1974	4.09	3.46	2.58	0.42	0.69	1.72	1.38	3.64	0.53	18.86
1975	2.26	2.03	1.40	0.48	0.29	1.31	1.11	2.87	0.47	12.79
1976	2.78	3.53	1.59	0.52	0.22	1.74	1.45	3.99	0.33	16.48
1977	3.71	3.48	1.43	0.42	0.31	1.36	1.29	3.78	0.30	16.58
1978	4.30	3.77	1.84	0.73	0.38	1.36	1.62	5.40	0.32	19.99
1979	5.28	3.27	2.12	0.44	0.41	1.03	1.88	1.79[a]	1.18[a]	17.40[a]
1980	6.29	2.27	1.34	0.62	0.32	0.52	1.66	1.41[a]	0.90[a]	15.32[a]
1981	4.20	1.69	1.08	0.49	0.17	0.43	1.28	1.44[a]	0.90[a]	11.68[a]

[a] The definitions of and reporting practices for the chemical categories changed in 1979. As a result, the chemical end use and total consumption data are not comparable with those for earlier years.

SOURCE: Charles River Associates, Inc., *Effects of the 1978 Katangese Rebellion on the World Cobalt Market*, report prepared for the Office of Technology Assessment, December 1982.

Figure 4-3.—Estimated Price Effects on U.S. Cobalt Demand



SOURCE: Charles River Associates, Inc., *Effects of the 1978 Katangese Rebellion on the World Cobalt Market*, report prepared for the Office of Technology Assessment, December 1982.

nets for such items as television, radio, and phonograph loudspeakers, telephone receivers and ringers, electrical meters, and automobile speedometers were an important use of cobalt, accounting for 20 percent of U.S. consumption. By the end of 1979, ceramic magnets had replaced 70 percent of cobalt-bearing Alnico magnets in loudspeakers. Moreover, the Bell system announced in 1979 that it was changing to alloys with lower cobalt content for telephone equipment, with savings of 100,000 pounds of cobalt per year. Much of the change in material for magnets is probably irreversible. Ferrite (ceramic) magnets are cheaper than cobalt, and now that the redesigning and retooling for the change has been done, there is little reason to change back.

On the other hand, demand for cobalt for superalloys in jet engines did not decline at all. Despite the high prices, superalloys demand continued to rise for 2 years until dampened by the recession in 1981. The boom in aerospace had led the 1978 surge in demand for cobalt, and jet engine manufacturers led the scramble for supplies when fears of a shortage rose. These manufacturers could do little in the short run to substitute other materials for cobalt superalloys in gas turbines for jet engines. Only after the most exacting, expensive qualification program can new alloys be used in jet engines. In some cases, however, different alloys had already been tested, and were adopted. For stationary gas turbines (e.g., for electrical power and pumping engines) the requirements are not so stringent, and some manufacturers were able to use other alloys for turbine parts. These substitutions, adopted over 3 years, probably saved about 10 percent of the cobalt that would otherwise have been used for superalloys, and the changes were probably permanent.[34]

Another leading use of cobalt in the United States is for hardfacing material, which, welded to a base material, provides a layer resistant to corrosion and wear (e.g., in engine valves, chainsaws, and earth-moving equipment). Some users of cobalt for hardfacing switched to nickel alloys. In Europe, where cobalt is used much more extensively in tool steels than it is here, users changed to cobalt-free tool steels. Consumption of cobalt for driers of inks and paints dropped 10 to 30 percent as users switched to manganese and zirconium as partial substitutes for cobalt. Substitutions for cobalt as a binder for carbide cutting materials were not very successful, but recent technological advances had made recycling more feasible, and these users did recycle. No replacements were immediately available in the short run for cobalt catalysts, although nickel-molybdenum catalysts may eventually displace some cobalt consumption for catalysts in the future.[35]

Recycling rose dramatically during the cobalt shortage. Everyone in the superalloy pipeline, from alloy producer to gas turbine manufacturer, began to recycle cobalt. This meant carefully segregating scrap by alloy specification, sending it back to the alloy melter and reusing it in the same grade. Possibly 10 to 25 percent of cobalt used in superalloys was recycled in this fashion. At the same time, methods for recycling all the materials in cemented carbide cutting materials (including cobalt) had just been brought to a state of economic feasibility. Methods widely adopted in 1978-79 continue to be used. It is estimated that most "new" carbide scrap (recovered from fabricators) is now recycled, and more old scrap (recovered from used products) is reused.[36]

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[34] Ibid., pp. 1-4 and 3-10.

[35] Ibid., p. 1-6.

Altogether, according to Bureau of Mines' data, recycling of cobalt increased 100 percent in the year 1978, and quickly rose from 4 percent of consumption in 1977 to nearly 11 percent in 1980, before tapering off to the 1982 level of about 8 percent. These figures understate the real extent of recycling, because they are limited to scrap that is purchased, and not all recycling is reported.

The U.S. Government never released cobalt from its stockpile throughout the period of high prices and tight supplies, since defense and essential civilian industries were getting what they needed and the stockpile, by law, can be used only to aid these industries during a national emergency. Cobalt-using industries added to their stocks during the 1978 panic and began drawing them down the next year.

The cobalt bubble burst in 1981. World production, spurred by high prices, continued to rise for the third year in a row in 1980. But with the 1981 recession, world cobalt demand fell drastically; in the United States, consumption dropped 24 percent. The producer price, pegged at $25 per pound in January 1981, was cut to $12.50 per pound in early 1982. Meanwhile, Zaire had contracted to sell the U.S. Government 5.2 million pounds of cobalt, for replenishment of the stockpile, at $15 per pound. Sixteen other producers had vied with Zaire to supply the government's stockpile purchases. By the end of 1982, the dealer market price sank below $5 per pound—considerably below the price in 1978 when the boom began. Cobalt prices stayed in the $5 to $6 per pound level until early 1984, when the producer price was increased to $11 to $12 per pound.

A modicum of diversity had entered the market between 1978 and 1982. A number of suppliers with new or expanded operations now stand ready to compete with Zaire. The bulk of world cobalt reserves are still in Zaire and Zambia, but Cuba, the Soviet Union, the Philippines, New Caledonia, and Australia all hold important reserves that are currently known and economic to mine. The United States also has substantial resources that are not now profitable to mine without a production subsidy.

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[36] Ibid., pp. 3-14 to 3-16.

The Effects of Supply Interruptions

These accounts of the few instances when U.S. imports of critically needed materials have actually been interrupted or threatened are interesting in their variety. The causes of interruption were different in each case, and the coping reactions, both by industry and by government, were varied enough to illustrate a wide gamut of responses to abrupt deprivation of supply.

The Soviet cutoff of manganese and chromium exports in 1949 was a Cold War political action, a response to the U.S. clampdown on export of manufactured goods, which in turn was a response to the Soviet blockade of Berlin. The Rhodesian chromium embargo in 1966, also political, was imposed by the United States in conformance with a United Nations resolution. The nickel strike of 1969 shut down supplies from the quintessentially "safe" foreign source—Canada—at a time when world nickel supplies had already been straightened for 3 years and Canada was then almost the sole U.S. supplier. The cobalt shortage of 1978-79 was a superheated case of a world surge in demand, combined with the abrupt removal of an important source of world supply (sales from the U.S. stockpile), which was aggravated by fears of insurrection and collapse of Zaire's mines (which never happened).

The response in the first two cases was, essentially, to find other foreign sources of supply. After the 1949 Soviet embargo, the U.S. Government actively sought alternate suppliers, offering loans for mine development, sending rail cars and providing steel for improved transportation. With the Rhodesian chromium embargo of 1966, the government sold excess chromium from the national stockpile, but otherwise took little active part, leaving industry to find alternate suppliers. That industry was able to do so quite readily, with little evidence of shortage, was due to several factors besides the stockpile sales: The Soviets promptly volunteered to serve as alternate suppliers of chromium to the United States (despite the Vietnam war which they opposed) and the United States was willing, for a time, to buy from them. Prices rose, drawing other suppliers like Turkey and the Philippines into production. The rapid adoption of the argon-oxygen-decarburization (AOD) process in stainless steel production allowed the substitution of South African chromium ore for Rhodesian ore. Finally, the Rhodesian embargo leaked. If France, Japan, Switzerland, and others had *not* bought what was probably Rhodesian chromium from South Africa and Mozambique, the alternate suppliers might have been hard put to provide the whole industrialized world with chromium.

The acute shortage of nickel that followed the Canadian strikes necessitated changed behavior from U.S. nickel users. They substituted other materials where they could, for example, replacing nickel stainless steel with chrome-manganese stainless steel (a technology that already existed). Users turned to nickel recycled from scrap, and they paid high prices for "gray market" nickel—once more supplied largely by the Soviets, despite the continuing Vietnam war. (In both the Rhodesian chromium and Canadian nickel episodes, it will be noted the Soviets behaved much more like enterprising capitalists than like ideological resource warriors.) An important factor in stopping the acute nickel shortage was the U.S. Government's release of a large quantity of nickel from the stockpile. The government had also responded to 3 years of tight nickel supplies by allocating what was needed to military users, and the set-asides were continued during the acute shortage.

As for the cobalt "shortage," users turned very quickly to substitutions and recycling. Under the spur of high prices, nonessential uses made way for essential. Government allocation was not needed to reserve cobalt for superalloys for military jet engines. Superalloy producers and users paid high prices and they recycled, while use of cobalt in magnets dropped by half. Ceramic magnets, for which the technology was ready, were substituted.

In all four cases, a long-lasting effect of the supply interruption was that new producers entered the market, and supply became more diversified. In the case of manganese, the U.S. Government and the World Bank deliberately encouraged new producers. In the other cases, shortages, rising prices, and eager buyers provided enough market incentive to draw new sources into production. Some substitutions (ceramic magnets) and some recycling (carbide cutting materials) adopted during the shortages appear to be permanent.

Another conclusion is worth noting: There is no one single answer to import vulnerability. In the episodes described above, multiple responses—some by government and some by industry—helped avoid a crisis or end shortages. On the government's part, there were active assistance to alternative suppliers, stockpile sales, and allocations to defense needs. On the private side, there were substitutions of materials (based on previous research and development [R&D]), recycling (also based in part on previous R&D), and a search for new sources of supply. In some cases, government and private actions were not so helpful—in fact, they were contributing causes, not solutions to the problems. The obvious example is the government's abrupt halt to sales of cobalt from the stockpile, and industry's panic buying of cobalt after the invasion of Zaire's Shaba province.

One response to import vulnerability that has rarely been used, except when begun in wartime, is government subsidies to high-cost domestic minerals producers. During the Korean war, which began just a year after the 1949 Soviet embargo of chromium and manganese, the government subsidized U.S. production of a number of minerals, including the two embargoed by the Soviets and cobalt. The last of the subsidies expired in the early 1960s. No one seriously suggested reviving subsidies for domestic producers of chromium in the late 1960s, when U.S. imports of Soviet chromium were once again rising following the Rhodesian embargo. The reason was the low-quality and limited supplies of domestic chromium ore and the high cost of producing it. Then, as now, even the best deposits of U.S. chromium would probably have cost two to three times as much as chromium mined abroad, with less favorable U.S. deposits still more costly.[37]

During the cobalt panic, subsidies for U.S. cobalt production were considered by Congress.[38] U.S. cobalt resources are considerably better than chromium resources, though they are still subeconomic. At congressional hearings in 1981, representatives of firms owning the most promising domestic sites estimated that cobalt prices ranging from $20 to $25 per pound would be needed to stimulate domestic production through government purchase contracts. Before any subsidies were decided on, the cobalt bubble had burst. By the end of 1982, the world cobalt price of $6 per pound (or less) was far below the estimated cost of producing U.S. cobalt. World prices have subsequently risen again (to $11 to $12 per pound in 1984), and one company has revised downward its estimate of the price needed for it to produce cobalt to about $16 per pound. Further discussion of subsidies for U.S. minerals production, in the context of broader materials policy, appears in the following section, as well as in chapters 5 and 8.

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[37] Information provided by John Morgan, Bureau of Mines, U.S. Department of the Interior. See also C.C. Hawley & Associates, Inc., subcontractor to Charles River Associates, *Strategic Mineral Markets and Alaska Development Potentials*, Policy Analysis Paper No. 82-12, prepared for the State of Alaska, Office of the Governor, Division of Policy Development and Planning (Juneau: 1982), vol. II, p. 1. This study estimated that the world chromium price would have to rise sixfold to stimulate production from known deposits in Alaska.

[38] U.S. Congress, Senate Committee on Banking, Housing, and Urban Affairs, Hearing on the Defense Production Act and the Domestic Production of Cobalt, 97th Cong., 1st sess., Oct. 26, 1981 (Washington, DC: U.S. Government Printing Office, 1982); Congressional Budget Office, *Cobalt: Policy Options for a Strategic Mineral*, cited in note 31.

Materials Policy

Over the past three decades, as episodes of tight supplies and high prices have come and gone, concern about a national materials policy has risen and ebbed. Three major commission studies, many other scientific and policy studies, three Federal laws stating materials policy, and several other relevant laws have addressed the question of how to assure a reliable supply, at reasonably stable prices, of the materials needed for this Nation's economy and defense.

All of the commissions recommended that the Nation seek materials wherever they may be found, at the lowest cost consistent with national security and the welfare of friendly nations. A policy of self-sufficiency was considered and rejected, most emphatically by the Paley Commission in 1952, and again quite explicitly by the Commission on Supplies and Shortages in 1976.

On the whole, the commissions' counsel in favor of interdependence has been heeded. The United States has, by and large, adhered to the "least cost" principle for materials supply for 35 years. The government has not only tolerated, but encouraged, U.S. consumption of minerals produced abroad. With low-cost loans, tax credits for taxes paid to foreign countries, and insurance against expropriation, it has helped U.S.-based firms to open mines in foreign countries, such as Australia, Brazil, and Peru. It has usually resisted proposals to protect the domestic mining industry by import quotas or other restrictions on trade and has subsidized domestic mining only rather briefly.

For security of supply, U.S. policy has been to rely mainly on stockpiles rather than on permanent subsidies of domestic production—again, a course which was urged by the commission reports. The first Federal law authorizing stockpiling of critical materials goes back to 1939, but actual accumulation of stocks was put aside during World War II and began in earnest during the Korean war. Large-scale purchases continued through the 1950s. Despite changes back and forth since then in stockpile policy, the Nation still has substantial amounts of many critical materials stored away.

Another recurring recommendation in the past three decades of studies, reports, and laws on materials policy has been to establish a focal point in the Federal Government for making comprehensive materials policy. This advice has been difficult to follow. One reason may be that materials shortages have been quite fleeting, and supplies are usually available when needed. Another is that materials policy is connected with other important policies—foreign, defense, taxation, environment, energy—which it is part of but does not dominate. Moreover, it is difficult to establish an overall "materials" or "nonfuel minerals" policy when the materials it is meant to cover are so numerous and so different from one another in the needs they meet, in critical importance, in availability of substitutes, and in the diversity and security of supply.

With the rising level of concern over U.S. import vulnerability, Congress (in 1980 and again in 1984) called on the Executive Office of the President to develop a coordinated materials policy. Questions of interdependence, self-sufficiency, and stockpile policy are also being reexamined. The following sections briefly survey the findings of the three major commissions on materials policy in the past 30 years and outline the main features of government policy and congressional actions on materials during the period.

Self-Sufficiency v. Interdependence

Many of those who believe that self-sufficiency is desirable subscribe to a broad-scale remedy of materials independence. They favor intensive exploration of most of the federally owned public lands, including wilderness, for minerals; tax breaks and government subsidies to encourage U.S. mining and minerals processing; and relaxation of strip mine controls, mine health and safety regulations, and clean air and water standards, which they blame for putting U.S. mining industries at a disadvantage vis-a-vis foreign competitors. On the other hand, critics of minerals independence say that an effort to replace imports with high-priced domestic minerals would raise the cost of finished goods, escalating prices at home, and making it harder for American products such as steel and autos to compete with foreign goods.

Despite the low quality of some U.S. mineral resources, the Nation could probably achieve significant domestic production in most minerals if it were willing to pay a high enough price. Part of the price might be greater environmental degradation and higher energy use, as well as higher dollar costs. Another cost might be a greater degree of government management of the minerals market and strains with European and Japanese allies, whose import dependence for 36 important nonfuel materials is considerably greater than that of the United States.

U.S. import dependence is often compared unfavorably with the Soviet Union's high degree of self-sufficiency in minerals. The Soviet Union has long followed a deliberate policy of supplying its own resource needs and, when forced to rely on foreign sources, has imported mainly from allies and neighbors. The result

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[*] The Office of Technology Assessment analyzed some aspects of the U.S. steel industry in its 1980 report, *Technology and Steel Industry Competitiveness*, OTA-M-122 (Washington, DC: U.S. Government Printing Office, June 1980).

is that the Soviets are net importers of only 11 of 35 important nonfuel minerals, and for only four—bauxite and alumina, barium, fluorine, and cobalt—is import dependence as high as 40 to 60 percent.

If the United States opts for a policy of minerals self-sufficiency instead of the traditional one of interdependence in a world free market, such a policy could require the United States to isolate itself from that market. Unless the government imposed export controls to keep domestic supplies inside the United States, U.S. trading partners could bid up the price and buy "U.S." minerals in times of shortages. In times of minerals abundance and low world prices, either U.S. mines would have to be subsidized or import controls imposed (like the pre-1973 oil import quotas) or both. In all these cases, economic and political stresses can be foreseen.

Commission Studies

President's Materials Policy Commission (Paley Commission)

The President's Materials Policy Commission, named for its chairman, William S. Paley, was established by President Truman in January 1951 during the early months of the Korean war. It was a time when a precipitate rise in military demands, added to an expanding post-World War II civilian economy, had caused tight supplies and shortages. The realization had dawned that materials usage worldwide was on an upward spiral. Reflecting a sense of crisis about the continued supply of enough materials to sustain the Nation's military security, civilian welfare, and economic growth, President Truman said in his charge to the Commission:

> By wise planning and determined action we can meet our essential needs . . . We cannot allow shortages of materials to jeopardize our national security nor to become a bottleneck to our economic expansion.[40]

The Commission's report, *Resources for Freedom*, published in June 1952, was colored with the same tone of strenuous response to a serious challenge. The Commission set for itself this question: "Has the United States the material means to sustain its civilization?"[41] It noted that the United States had already outgrown its resource base and had become a "raw materials deficit" Nation. At the core of the materials problem it put "growth of demand"—growth not only in the United States but also among the free world allies and in the former colonies seeking to industrialize rather than export raw materials.

To assure the material basis for security and growth the Paley Commission saw interdependence as the best answer. "The United States must reject self-sufficiency as a policy," the Commission said, "and instead adopt the policy of the lowest cost acquisition of materials wherever secure supplies may be found: self-sufficiency, when closely viewed, amounts to a self-imposed blockade. . . "[42]

The Commission emphasized policies that would encourage investment by American business in mineral development in foreign countries and would remove barriers to trade. It also urged U.S. loans and technical assistance, in addition to international help, for indigenous investment in mining, especially in poor countries. Besides these policies to promote "least cost" production worldwide, the Commission also stressed the value of greater efficiency of use, substitution of more abundant materials for scarce ones, and the expansion of domestic supplies by "pushing back the technological, physical, and economic boundaries that presently limit supply."[43]

Even to protect national security, the Commission regarded a quest for self-sufficiency as "fallacious and dangerous." For many materials, the Commission said, "self-sufficiency is either physically impossible or would cost so much . . . that it would make economic nonsense."[44] Instead, the Commission suggested a range of policies to raise the Nation's preparedness against a possible cutoff of materials critical to the Nation's defense.

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[40] The President's Materials Policy Commission, op. cit., p. IV.

[41] Ibid., pp. 1, 6, and passim.

[42] Ibid., p. 3.

[43] Ibid., p. 8.

[44] Ibid., p. 157.

To assure supply, the Commission strongly urged stockpiling. Also, it recommended several measures to prepare emergency sources of production, including: setting aside "in-the-ground" domestic reserves of key minerals, especially limited or low-grade deposits; developing and maintaining ready-for-use technology to produce low-grade deposits; and preparing processing facilities and transportation for the in-the-ground reserve. On the demand side, the Commission recommended the design of military products to use abundant rather than scarce materials, and the preparation of "standby" designs for use in extremity, substituting available materials for scarce ones that would otherwise be preferred.[45]

The Paley Commission report noted the lack of a coordinating body for materials policy, and suggested that the National Security Resources Board, in the Executive Office of the President, undertake the role.[46] However, the Board was soon abolished by Congress as fears of "running out" of material, which had prompted the establishment of the Paley Commission, died down. No other body was given the policy coordination task.

Indeed, after a brief burst of public attention, the Commission's report fell into obscurity. True, the interdependence policy strongly urged by the Commission has generally guided the government's actions since then. One administration after another has followed the Commission's advice in such matters as negotiation of treaties to support freer trade and provision of government insurance for private businesses investing in resource development abroad. But for the most part, the detailed recommendations of the Commission's report were ignored. One of the very few concrete responses by anyone was the creation of a nongovernment institution to monitor materials supply and demand—Resources for the Future, which is largely funded by the Ford Foundation.

Photo credit: U.S. Navy

One mission of U.S. Navy frigates such as the USS Antrim (FFG-20) is to protect the flow of strategic materials to the United States

The reasons for the report's neglect are not hard to find. First, the party in power changed; President Eisenhower won the 1952 election, and the Republicans took control of Congress for the first time in 20 years. More important, wartime shortages of materials turned to glut with the end of the Korean war. When President Eisenhower appointed a Cabinet committee in 1954 to examine minerals policy, the question was not how to assure enough supply, but how to help rescue the ailing domestic mining industries. (As discussed below, the Eisenhower Administration's response was to guarantee purchases of minerals for an expanded strategic stockpile.)

National Commission on Materials Policy

For most of the 1950s and 1960s, adequacy of materials supply was a quiescent issue, despite some bottlenecks and shortages as Vietnam war needs expanded. Supplies of minerals rose comfortably with demand, and real prices generally remained stable or fell throughout most of the period. Production of aluminum rose enormously (over fourfold) relieving pressure on other structural and electricity-conducting materials, and petrochemical-based plastics replaced a number of the conventional metals.

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[45] Ibid., ch. 27-30.

[46] Ibid., p. 171.

Toward the end of the 1960s, Congress and the public began to look at materials issues in a new perspective—i.e., in relation to conservation of resources and environmental quality. In 1970, Congress created a new materials policy commission as a direct outgrowth of its work on recycling of materials and recovery of energy from waste. Former Senator J. Caleb Boggs was a sparkplug of the renewed congressional interest in materials policy and its connections with energy and the environment. A series of biennial National Materials Policy Conferences was begun in 1970 at his request, and he introduced the legislation creating a new materials commission.[47]

The background of the commission's formation was this: While considering an innovative Federal law on solid waste (The Resource Recovery Act of 1969), the Senate Committee on Public Works asked for a study on a national policy for handling materials, from extraction to disposal. The ad hoc committee doing the study recommended a fresh look at materials problems as a whole and a new national commission.[48] The next year, Congress amended the Resource Recovery Act, incorporating in it the National Materials Policy Act of 1970 and creating the National Commission on Materials Policy (NCMP) with this objective:[49]

> . . . to enhance environmental quality and conserve materials by developing a national materials policy to utilize present resources and technology more efficiently, and to anticipate the future materials requirements of the Nation and the world, and to make recommendations on the supply, use, recovery and disposal of materials.

The Commission's report, *Material Needs and the Environment Today and Tomorrow*, issued in 1973, recommended striking a balance between the need to produce goods and the need to protect the environment. In particular, it urged that environmental costs be included in reckoning the costs and benefits of materials production. While calling for "orderly" development of resources, the Commission also strongly urged conservation through recycling and greater efficiency of use. To carry out these policies, the NCMP made 198 detailed recommendations in 10 major areas.[50]

The "traditional U.S. economic policy" of buying materials at least price was reaffirmed by this Commission. The policy was given credit for providing reasonably priced goods to consumers and keeping U.S. goods competitive in world markets. However, the Commission qualified its support of the least-cost interdependence policy to a degree. It argued that some U.S. minerals industries might need a limited amount of protection from competition with "subsidized" foreign producers.[51]

As for national security, the Commission recommended that where problems of supply are foreseen, the United States should foster domestic production, diversify sources of supply, develop special relations with reliable foreign sources, increase the dependence of supplying countries upon continuing U.S. goodwill, and find substitute materials.[52] The Commission gave little attention to stockpiling, possibly because the imported material of greatest concern at the time was oil, and stockpiling oil is far more expensive and cumbersome than storing most nonfuel minerals. (The NCMP's charge included energy; it defined materials as all natural resources intended for use by industry, except for food.)

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[47] In response to a request by Senator Boggs, the late Dr. Franklin P. Huddle, Senior Specialist with the Congressional Research Service of the Library of Congress, organized a series of biennial National Materials Policy Conferences. The conferences, under the auspices of The Engineering Foundation, were held at New England College, Henniker, NH. They are widely known as "the Henniker Conferences."

[48] U.S. Congress, Senate Committee on Public Works, *Toward a National Materials Policy*, committee print, 91st Cong., 1st sess.

[49] Title II of the Resource Recovery Act of 1970 (Public Law 91-152), entitled the National Materials Policy Act of 1970, sec. 202.

[50] National Commission on Materials Policy, *Materials Needs and the Environment Today and Tomorrow* (Washington, DC: U.S. Government Printing Office, 1973), pp. 1-4, 1-5, and ch. 6.

[51] Ibid., pp. 9-8 through 9-10.

[52] Ibid., p. 9-26.

Like the Paley Commission 20 years earlier, the NCMP urged that a high-level government body oversee Federal materials policy. It proposed a Cabinet-level agency—possibly a new Department of Natural Resources—to plan and execute comprehensive policy for materials, energy, and the environment.[53]

While the Department of Natural Resources was not created, the report of the NCMP received considerably more official attention than its predecessor had. At the time the report came out, interest in materials issues had quickened. A world economic boom was on the upswing, and some shortages of materials had begun to appear. The Club of Rome's widely read report *The Limits to Growth* (published in 1972),[54] suggested that world demand for materials, increasing exponentially, would outrun the planet's finite supplies, leading to a devastating collapse of world economies in the 21st century. In this atmosphere, interest in the Commission's report ran high.

The Commission's report was the springboard for hearings before the Senate Subcommittee on Minerals, Materials, and Fuels,[55] and materials issues were the subject of other congressional hearings and reports;[56] the Office of Technology Assessment added a program to assess materials issues. Other congressional agencies—the General Accounting Office and the Congressional Research Service—undertook studies on materials issues.[57] The National Academy of Sciences issued numerous reports commenting on and related to the NCMP report.[58] Finally, a most concrete result was the hearings and work done by the Senate Committee on Public Works on resource recovery and recycling,[59] which eventually led to passage of the Resource Conservation and Recovery Act of 1976.

National Commission on Supplies and Shortages

When the National Commission on Materials Policy issued its report in mid-1973, OPEC was a name known only to specialists. Oil prices had just begun to rise as a result of cartel control. Within a year, OPEC had not only quadrupled prices, but for a time had denied its members' oil to the United States and The Netherlands. In addition, the world economic boom, by then 2 years old, had created shortages of many industrial materials. Prices of commodities from rubber and oil to scrap steel and copper bounded upward, and industries had real difficulty in getting the aluminum, copper, chemicals, petrochemicals, steel, and paper that they needed. The influence of *The Limits of Growth*, with its projections of world resource exhaustion and economic collapse, was at its height. To some people, the shortages of 1973-74 seemed early indications of just such a collapse.

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[53] Ibid., p. 1-8 and ch. 11.

[54] Donella H. Meadows, et al., *The Limits to Growth* (New York: Universe Books, 1972).

[55] U.S. Congress, Senate, Committee on Interior and Insular Affairs, Subcommittee on Minerals, Materials and Fuels, Hearings, Oct. 30, 31, and Nov. 1, 1973, committee print.

[56] See, for example, U.S. Congress, Senate, Committee on Public Works, *Resource Conservation, Resource Recovery, and Solid Waste Disposal*, committee print, 1973.

[57] See, for example, the reports of the biennial Henniker conferences, which were organized by the Congressional Research Service, and U.S. Congress, House of Representatives, Committee on Science and Astronautics, *Industrial Materials: Technological Problems and Issues for Congress*, committee print, 1972, prepared by Dr. Franklin P. Huddle of the Congressional Research Service. The General Accounting Office undertook studies that led to such reports as *Federal Materials Research and Development: Modernizing Institutions and Management* (Washington, DC: U.S. Government Printing Office, 1975). The Office of Technology Assessment Materials Program undertook a broad range of studies too numerous to cite.

[58] Reports produced by the National Academy of Sciences and affiliated organizations included: National Academy of Sciences/National Academy of Engineering, *National Minerals Policy*, Proceedings of a Joint Meeting, Oct. 25-26, 1973 (Washington, DC: The Academy, 1975); National Academy of Sciences, *Man, Materials, and the Environment*, report of the Study Committee on Environmental Aspects of a National Materials Policy (Washington, DC: The Academy, 1973); National Academy of Sciences, Committee on the Survey of Materials Science and Engineering, Materials and Man's Needs (Washington, DC: The Academy, 1974); National Academy of Sciences, Committee on *Mineral Resources and the Environment* (COMRATE), Mineral Resources and the Environment (Washington, DC: The Academy, 1975).

[59] U.S. Congress, Senate Committee on Public Works, *Hearings*, June 11-13, July 9-11, 15-18, 1974, committee print.

In this crisis atmosphere, national attention again fastened on the adequacy of material supplies. While two House committees were preparing reports on the subject—one on America's resource needs and import dependence and the other on world resource "scarcities"[60] —former Senators Mike Mansfield and Hugh Scott formed a joint Executive Congressional Leadership group to discuss threatened shortages of natural resources, raw materials, and agricultural commodities. Out of this group emerged legislation (an amendment to the Defense Production Act of 1950, in September 1974) creating the National Commission on Supplies and Shortages.

The Commission was instructed to look at four principal issues: the possibility of resource exhaustion, the consequences of the Nation's growing dependence on imported materials, the ability of the free market to deal with shortages, and the adequacy of government mechanisms for handling materials problems.

The Commission's report, *Government and the Nation's Resources*, issued in 1976, concluded that the country's ability to meet its material needs was in no imminent danger.[61] It said that:

- resource exhaustion was not a serious threat to economic growth for the next quarter century "and probably for generations thereafter";
- U.S. dependence on imported materials other than oil was growing only gradually and manageably;
- cartel control of nonfuel minerals was unlikely and embargoes directed against the United States "only remotely conceivable," and that neither was any real threat to the American economy; and
- the widespread severe shortages of 1973-74 were a temporary phenomenon due to the world surge in demand, to lagging investment in materials industries for a few years before the boom, and to a "shortage mentality" that led to panic buying and hoarding of materials by industries in many countries.

These conclusions added up to strong, continued support for the principle of free trade and interdependence.[62]

The Commission stated that it found no instances of import dependence that would justify the costs and rigidities of placing restrictions on imports. Instead, to cope with interruptions of supply that might result from civil disorders in producing regions or, possibly, from price-gouging by producers, the Commission recommended stockpiling as "the universal antidote."[63] The Commission supported a strictly limited use of the strategic stockpile for economic purposes during a sudden disruption of supply of critical materials to keep the civilian economy as well as defense industries on an even keel. However, the Commission said, stocks should *not* be sold simply to influence prices in the absence of a supply disruption (as the Johnson Administration had done in the 1960s—see the discussion below).[64]

Underlying many of the Commission's conclusions was confidence in the ability of market forces to bring forth adequate materials for the world's economies and to right imbalances within a reasonable time. Many of the recommendations amounted to "hands off" the market. For example, in its consideration of recycling, the Commission suggested the removal of depletion allowances for minerals, which favor virgin ore over recycled materials—but no subsidies for recycling either.[65] In a similar vein, the Commission was cautious about recommending government funding for R&D for alternative supplies, conservation, and substitute materials. Recognizing that government does have a role to play (especially in basic research), the Commission suggested that more knowledge is needed of what motivates industry to commit R&D funds before government rushes in to fill the breach.[66]

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[60] U.S. Congress, House of Representatives, Ad Hoc Committee on the Domestic and International Monetary Effect of Energy and Other Natural Resource Pricing, *Meeting America's Resource Needs*, a report to the Committee on Banking and Currency (Washington, DC: U.S. Government Printing Office, 1974); U.S. Congress, House of Representatives, Committee on Foreign Affairs, *Global Commodity Scarcities in an Interdependent World* (Washington, DC: U.S. Government Printing Office, 1974).

[61] National Commission on Supplies and Shortages, *Government and the Nation's Resources* (Washington, DC: U.S. Government Printing Office, 1976).

[62] Ibid., pp. x-xii, chs. 2, 3, and 4, especially pp. 22-23 and 38-39.

[63] Ibid., p. 39.

[64] Ibid., ch. 7.

[65] Ibid., p. 166.

The Commission recognized political obstacles to private investments in the world's minerals, such as the threat of expropriation, but called attention to existing measures to lessen the obstacles—measures such as government insurance for foreign investment, international disputes settlement and investment codes, and World Bank investments in developing countries. The Commission also expressed confidence "that private investors and Governments will find ways to adjust to political and economic realities."[67]

The Commission noted that complicated problems, like the rapid growth of world population, the unequal distribution of world resources, and the sometimes unexpected and unwanted byproducts of technological advance might require an increasing degree of government sophistication and management. It found room for improvements in the adequacy of the U.S. Government institutions to deal with materials issues. It also proposed practical changes in data collection and analysis and suggested the creation of a small, high-level corps of professionals to monitor specific industries and economic sectors and to develop a comprehensive picture of how government policies combine to affect basic industry and the national interest. However, the Commission recommended against seeking a "coordinated materials policy" as an end in itself, because materials policy affects and is affected by many other policies on matters of equal or greater importance.[68]

By 1976, when the Commission published its report, the materials shortages that were so worrisome at the time of its creation had disappeared. Minerals activity had slid from the peak of high prices and tight supplies of the first half of 1974 to the trough of a world business recession, following the OPEC oil price hike.

Under the circumstances, the Commission's more astringent suggestions for "hands off" the market (e.g., removal of the percentage depletion allowance for new minerals) were coolly received. In fact, there was some sentiment in Congress (especially among members from the western mining States) for much more active government support of the now-depressed and always volatile domestic mining industry than anything suggested by the noninterventionist report of this Commission. Some were also dissatisfied with the limited backing the Commission had given to the idea of "comprehensive" or "coordinated" materials policy.[69] Altogether, the report got little official response. Changes in the Commerce Department's economic analysis toward stronger analysis by the industrial sector was perhaps the principal result.

Once again, a Commission report on materials coincided with a change of the party in power. Within a month of President Carter's taking office, former Representative James Santini and 42 other members of the House of Representatives wrote to the President expressing concern that the Nation's policies were adversely affecting nonfuel minerals production, asking for a "balanced" national minerals policy, and proposing a special minerals advisor in the Executive Office of the President. In December of that year, the President ordered a government review of nonfuel minerals policy. The results, as noted below, were minimal; the policy review was never completed. At the end of the Carter presidency, demands by the industry and interested members of Congress for a "national minerals policy," support for the minerals industry, and a special minerals advisor to the President were stronger than ever.

As the brief history outlined here suggests, Commission reports on materials policy and government actions have not always meshed. This is perhaps predictable, given the cyclical nature of the minerals industry. When commissions are formed, one set of problems may be dominant (e.g., shortages and high prices); but economic conditions may be quite different a year or two later when the report is issued, so that the problems may look quite different (e.g., idle domestic capacity, inadequate investment, "unfair" foreign competition). Also worth noting is that commissions may be rather insulated from political concerns, while the government that responds to them is not.

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[66] Ibid., pp. 182-184.

[67] Ibid., p. 46.

[68] Ibid., chs. 5 and 6.

[69] For this point of view, see U.S. Congress, House of Representatives, Committee on Interior and Insular Affairs, Subcommittee on Mines and Mining, *U.S. Minerals Vulnerability: National Policy Implications*, committee print, 96th Cong., 2d sess.

Thus, it is not too surprising that of the hundreds of detailed recommendations made by the three major materials commissions, Congress and the various administrations of the past three decades have specifically adopted only a few. By and large, both the executive branch and the Congress have steered a course —from tax laws to international trade treaties— that is consistent with the interdependence policy recommended by the commissions. But there have been exceptions. And in general, congressional and other government actions have followed their own agendas, rather than responding directly to commission recommendations. Thus, government actions on materials issues over the past 30 years are discussed separately from the story of the commissions reports.

Congressional Actions and Government Policies

Two strands in materials policy, besides the general support for free world trade, have won consistent backing from Congress over a number of years. One is the building of a strategic stockpile, a policy that is now nearly 45 years old. The other is high-level government oversight of a "comprehensive" materials policy, an idea at least as old as the Paley Commission, but insistently put forward by Congress since about 1970.

A program that promoted and subsidized domestic minerals industries—an exception to the least-cost, interdependence policy—began during the Korean war and was actively pursued for a few years thereafter. The program died out in the 1960s, but the law that authorized it, the Defense Production Act of 1950, remained on the books and interest in the program has been revived as a means to reduce import dependency.[70] Congress has repeatedly extended the law, most recently in 1984. Production subsidies for cobalt were considered in deliberations about this extension, but are considered unlikely in fiscal years 1985 and 1986. (See chs. 5 and 8 for further discussion.)

Stockpiling and Subsidies

Stockpiling originated in 1939, when, on the eve of world war, Congress passed the Strategic Materials Act. The Act authorized the government to list materials essential for industry and defense and to buy them for a strategic stockpile. Wartime needs soon overwhelmed the stockpiling program. The postwar Strategic and Critical Materials Stock Piling Act of 1946 restated the goal of preparing for an emergency by building stockpiles, and by 1950 some $1.6 billion worth of stocks had been acquired. This was less than halfway to the objective then in effect of $4.1 billion. With the outbreak of war in 1950, Congress provided funds for further major additions to the stockpile.

The Korean war prompted the passage of the Defense Production Act of 1950. Besides authorizing government priorities and allocations of materials, the Act provided financial assistance for expanding domestic productive capacity, including facilities to produce critical nonfuel minerals. During and after the Korean war, purchase agreements, floor prices, and loans or loan guarantees under the Act promoted a doubling of U.S. aluminum production, a 25-percent increase in U.S. copper mining, and a fourfold expansion of tungsten mining. Assistance under the Act also encouraged the startup of U.S. nickel mining and titanium processing and fostered domestic production of other minerals, including manganese, cobalt, and chromium. The gross outlay of the government for these programs was $8.4 billion; with the payback of loans, the ultimate direct cost has been estimated as $900 million.[71]

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[70] Certain parts of the law that were tailored specifically to wartime needs (authorization for price, wage, and credit controls and for settlement of labor disputes) lapsed in 1951.

[71] U.S. Congress, Senate Committee on Banking, Housing, and Urban Affairs, *Defense Production Act Extension of 1981*, report to accompany S.1135 (Washington, DC: U.S. Government Printing Office, 1981), p. 3.

With the end of the war, many of the minerals supported by government programs were being produced in greater quantities and at higher prices than the civilian economy could absorb. Purchases for the strategic stockpile drained off some of the excess. The Eisenhower Administration continued to build stockpiles throughout most of the 1950s, partly to bolster mining industries the government itself had created, but also because President Eisenhower strongly believed in stockpiles as insurance.[72]

Government support proved to be a mixed blessing for some mining industries. Companies drawn into production by the combination of subsidized loans, purchase agreements, and large stockpile purchases were left stranded when stockpiles became filled, government purchases ceased, and subsidies were withdrawn. Tungsten mining in particular was on a roller coaster.[73]

A vital constituent for many superalloys and a widely used material for cutting tools, tungsten was selected as a critical material to be stockpiled, with a goal of 146 million pounds set in 1950. By 1955, government financial assistance, combined with stockpile purchases at high prices, had drawn more than 700 U.S. mines (mostly small ones) into operation. The government stopped stockpile buying of tungsten in 1957, after stocks had swollen to 210 million pounds—enough for 6 years consumption by the entire Western World, or 10 years of U.S. consumption.

In 1958, the Eisenhower Adminstration reduced the requirement for stockpiled materials from the amount needed to sustain the Nation for a 5-year war to enough for 3 years. Three-quarters of the tungsten holding was thereupon declared excess. In 1962 the Government began to sell tungsten stocks. Prices tumbled by two-thirds, and all but 2 of the 700 domestic mines ceased operations. Not until the late 1970s did the domestic tungsten industry resume growth.

In the 1960s, during the Kennedy and Johnson years, the government sold a number of commodities from the stockpile that were now in excess of the 3-year requirement—often using the sales as part of a strategy to control inflation or reduce budget deficits. In 1973, the Nixon Administration further reduced the stockpile requirements, from 3 years' sustenance to one, with the result that still greater quantities of stockpiled material were now officially declared excess.

At this point, Congress balked. The House Subcommittee on Seapower and Strategic Critical Materials questioned the new policy, threatened to block sales of stockpiled materials, and demanded a thorough study of stockpile policy. The Ford Administration complied, conducting an interagency review under the White House National Security Council. In 1976 the Administration announced a new stockpile policy based on planning to support defense and essential civilian needs for the first 3 years of a national emergency of indefinite duration. A few months after taking office, President Carter reaffirmed the Ford policy.

In 1979 Congress took stock. At this point, 40 years after the stockpile was established, the publicly owned stockpile was large but out of balance. The inventory was valued at $10.5 billion, of which $4.9 billion (or 47 percent) was excess to goals based on the 3-year requirement. But needs for acquisition amounted to $12.9 billion—more than the value of stocks on hand.[74]

Dissatisfied with the fluctuations in stockpile policy over the 40 years, Congress now wrote more explicit policy guidance and stockpile requirements into law. In the Strategic and Critical Materials Stock Piling Revision Act of 1979, Congress stated that the purpose of stockpiles is for the defense of the United States, not to control commodity prices. It also wrote into law that stockpiles should be sufficient to sustain the country's military, industrial, and essential civilian needs for at least 3 years, and that goals based on this requirement cannot be changed without prior notice to Congress. Finally, Congress set up a stockpile transaction fund, so that the proceeds from the sale of excess materials can be used to buy materials that are needed, rather than going back into the general Treasury funds.

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[72] Franklin P. Huddle, "The Evolving National Policy for Materials," Science 191, p. 655 (Feb. 20, 1976); also, A. E. Eckes, Jr., *The United States and the Global Struggle for Minerals* (Austin: University of Texas Press, 1979), p. 215.

[73] Most of the material that follows on the tungsten industry from 1950 to 1970 is drawn from Konrad J. A. Kundig, "The Tungsten Market—From Chaos to Stability," *Journal of Metals*, May 1981, pp. 42-47.

[74] Information on stockpile holdings was provided by the Federal Emergency Management Agency.

A "National Materials Policy"

Meanwhile, at the end of the 1960s, Congress also turned its attention to the question of a broad Federal responsibility for materials policy, acting initially in the area of minerals policy. The Mining and Minerals Policy Act of 1970 was inspired by the National Environmental Policy Act of 1969, and was intended to provide similar guidance and goals in its own area.[75]

The Act declared it the national policy to foster and encourage: 1) the development of economically sound and stable domestic mining, minerals, and minerals reclamation industries; 2) the orderly and economic development of domestic mineral resources, reserves, and reclamation of minerals to help satisfy industrial, security, and environmental needs; 3) mining, mineral, and metallurgical research, including use and recycling of scrap; and 4) the study and development of methods for disposal, control, and reclamation of mineral waste products and mined land to lessen adverse impacts. The Secretary of the Interior was put in charge of advancing national minerals policy, as set forth in the law. He was required to report each year on the state of the domestic mining and minerals industry, and to recommend any laws needed to carry out the national policy. Beyond that, the law called for no specific actions.

Few identifiable actions were undertaken in response to the act. The Bureau of Mines used the language of the law to support funding requests for research in recycling and safe disposal of mine wastes, but no remarkable changes in funding priorities resulted. The Secretary of the Interior's first two annual reports (in 1972 and 1973) viewed with alarm problems of the U.S. minerals industry and the increasing U.S. import dependence on fuel and nonfuel minerals, but made few recommendations for changes in the law to carry out a national minerals policy. (One of the few changes recommended was to amend the antitrust laws to allow joint ventures for mineral research.) Later annual reports took a less alarmist view of the rising import dependence for fuel and nonfuel minerals, most of which was actually due to oil imports. The 1975 report, for example, said that problems arise from increasing imports "only when foreign sources become unreliable." Especially in 1978 and 1979, the document failed to advocate the strong government support of the domestic minerals industry that sponsors of the law had evidently envisioned.

By the mid-1970s strong supporters of the mining industry in Congress had become concerned about what they saw as continuing neglect of national minerals policy by the executive branch. Displeased with the rather laissez-faire conclusions of the Commission on Supplies and Shortages, they urged the new Carter Administration to undertake a fresh review of national nonfuels mineral policy. President Carter responded in December 1977, appointing Secretary of the Interior Cecil B. Andrus chairman of an interdepartmental policy review committee.

The nonfuel minerals policy review gave even less satisfaction to advocates of a "national minerals policy." The review ultimately foundered, going no further than a partial draft report in 1979.[76] It had suffered a fate common for interdepartmental task force efforts—consignment to lower rungs of the bureaucratic ladder and a watering down of controversial issues. In hearings held around the country on draft portions of the report, the document was criticized by all sides—industry, environmental groups, and consumer organizations.

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[75] House Subcommittee on Minerals and Mining, *U.S. Minerals Vulnerability*, pp. 16-18. See the Committee's comparison of environmental laws with the Mining and Materials Policy Act of 1970, which it viewed as the victim of neglect by the executive branch.

[76] U.S. Department of the Interior, "Report on the Issues Identified in the Nonfuel Minerals Policy Review," draft for public review and comment, August 1979.

A number of congressional and industry critics criticized the document on national security grounds. They linked together the issues of import dependence, the health of the domestic minerals industries, the Nation's need for strategic materials, and the threat of a "resource war."[77]

Aside from mining and minerals, Congress had yet to declare a statutory national materials policy. The Paley Commission, in 1952, had spoken of "a national materials policy for the United States" with an overall objective of insuring "an adequate and dependable flow of materials at the lowest cost consistent with national security and with the welfare of friendly nations." But the difficulties entailed in translating such recommendations into meaningful policy were formidable—given the diverse role that materials play in all aspects of society. When Congress, in 1970, enacted a National Materials Policy Act, it was for the purpose of developing such a policy (through Commission recommendations) rather than articulating one.

Nonetheless, throughout the 1970s, materials advocates both inside and outside the Congress had been laying the groundwork for a materials policy that would encompass a broad range of concerns—yet not be so broad as to be all inclusive. Some material policy concerns that were prominent in the early part of the decade became themselves the subject of separate legislation, thus making the task of what to emphasize in an overall national materials policy more manageable. Solid waste disposal—a dominant materials policy issue in the early 1970s—was perhaps the most conspicuous example. It still attracted considerable attention, but with enactment of the Resource Conservation and Recovery Act of 1976 its earlier prominence in the hierarchy of material policy concerns began to decline. Other concerns, such as import vulnerability, and the competitiveness of basic U.S. industry, had moved to the forefront.

Meanwhile, the House Committee on Science and Technology was working on legislation which emphasized the role of research and development in resolving material problems. Since the early 1970s, the Committee had become increasingly involved with the issue, releasing a series of background reports and holding hearings on various legislative proposals which had a science and technology component in implementing materials policy.

By the 95th Congress, these legislative concepts had begun to crystallize, so that one member of the committee could speak, in mid-1977, of acting in "concert with other committees of both Houses" to begin "to establish an orderly, effective national materials policy."[78] Several members of the committee had introduced bills which, while differing in detail, had themes in common.[79] First, the bills proposed a statutory materials policy. Second, implementation of the policy would be achieved through focusing Federal materials R&D activities. Third, they emphasized the need for greater involvement of the Executive Office of the President (through the Office of Science and Technology Policy (OSTP) or a new organization in the EOP) in materials decisionmaking.

None of these bills passed the 95th Congress, but the hearing process helped to further refine the basic legislative concepts and build a greater degree of consensus about components of national materials policy legislation. While expressing agreement with the overall objective of these bills, the Carter Administration was not convinced that new legislation was necessary. OSTP, it said, already had the authority to achieve those goals, and moreover its nonfuel mineral policy review, and other initiatives in areas of basic innovation and improved coordination of R&D would provide the needed direction for Federal policy without additional legislation.

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[77] U.S. Congress, House of Representatives, Committee on Interior and Insular Affairs, Subcommittee on Mining and Minerals, *Hearings*, Oct. 18, 1979 (Washington, DC: U.S. Government Printing Office, 1979), statement of Representative James D. Santini, Chairman. See also the testimony of E. F. Andrews, Vice-President, Allegheny Ludlum Industries, Inc.

[78] U.S. Congress, House Committee on Science and Technology Subcommittee on Science, Research and Technology, Hearings on a National Policy for Materials; Research and Resources, 95th Cong., 1st & 2d sess., June 29, July 13, 14, 1977; Feb. 28, Mar. 1, 2, and 6, 1978 (Washington, DC: U.S. Government Printing Office, 1978), pp. 1-2.

[79] Material policy bills introduced in the 95th Congress included H.R. 10859, H.R. 11203, and H.R. 13025.

The Administration's position became less persuasive in the 96th Congress, when its draft nonfuel mineral policy review came under considerable congressional criticism. With the reverberations of the cobalt price spike still shaking U.S. industry, the issue of import dependency was very much on the minds of legislators. Sponsors of materials legislation in the House saw an emphasis on science and technology as an important step toward reducing import vulnerability. At the end of 1979, the House, by a 398 to 8 vote, passed H.R. 2743, called the Materials Policy, Research and Development Act. The bill, originally introduced by Representative Don Fuqua, Chairman of the House Science and Technology Committee, reflected many of the basic concepts considered by the Committee in the 95th Congress—including a broad-based material policy, to be implemented through an improved executive branch decisionmaking process in regard to R&D activities.

After it was sent to the Senate, the House bill's basic framework was maintained, but its scope was enlarged as the bill moved through two Committees (Commerce, Science, and Transportation; and Energy and Natural Resources) to the Senate floor. New provisions were added which placed greater emphasis on materials import vulnerability, and the Departments of Defense, Commerce, and Interior were given important supporting roles in identifying vulnerability problems. In general, the Senate bill placed greater emphasis on minerals—thus bringing together in one piece of legislation the sometimes disparate concerns of the materials and minerals communities.

The bill was signed by President Carter on October 21, 1980, in the closing days of the 96th Congress.[80] The National Materials and Minerals Policy, Research and Development Act of 1980 (Public Law 96-479) declared:

> . . . it is the continuing policy of the United States to promote an adequate and stable supply of materials necessary to maintain national security, economic well-being and industrial production with appropriate attention to a long-term balance between resource production, energy use, a healthy environment, natural resources conservation, and social needs.[81]

The law spelled out a number of activities in furtherance of this national materials policy, to be undertaken by the President, his Executive Office, and various departments. It directed the President to submit a plan to Congress that would assure: policy analysis and decisionmaking on materials in the Executive Office of the President; interagency coordination of material policy at the Cabinet level; continuing long-range analysis of the use and supply of materials to meet national needs; and continuing consultation with the private sector on Federal material programs.

The law designated the Office of Science and Technology Policy, in the Executive Office of the President, to coordinate Federal materials R&D, emphasizing R&D to meet long-range material needs through annual assessments. Responsibility for several specific tasks was placed in various departments: Commerce, to do case studies of material needs (the aerospace industry was selected for the first study and the steel industry the next); Defense, to assess material needs critical to national security; and Interior, to improve the assessment of international minerals and to make better minerals data and analysis available for decisions on Federal land use, and to report on its activities in these areas.

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[80] For legislative history of Public Law 96-479, see House Report 96-272, Nov. 29, 1979 (House Science and Technology Committee); Senate Report 96-397, Aug. 13, 1980 (Senate Commerce, Science and Transportation Committee); Senate Report 96-937, Sept. 12, 1980 (Senate Energy and National Resources Committee; House debate and passage, *Congressional Record*, Dec. 4, 1979; Oct. 2, 1980; Senate debate and passage, *Congressional Record*, Oct. 1, 1980.

[81] Public Law 96-479, sec. 3.

In April 1982, President Reagan submitted the plan called for by the Act.[82] Dominating the plan was its emphasis on opening more of the federally owned public lands to minerals prospecting and development in order to "achieve a proper balance between wilderness and mineral needs of the American people." Another major theme was renewed and improved stockpiling. The President took credit for the first major stockpile acquisitions in 20 years—purchases of cobalt and acquisition of Jamaican bauxite by purchase, barter of agricultural products, and swap of excess stockpile materials. The President's report promised a thorough review of the quality of stockpiled materials, some of which are decades old.

Despite efforts by Congress to assure high-level coordination of national materials policy, the plan offered little that was new in this regard. National materials policy, it said, would be coordinated through the Cabinet Council on Natural Resources and Environment (as it had been since the early days of the Reagan Administration). No budget for a coordinated materials program was presented (even though the law requires one); the Cabinet Council needs only a "minimum administrative staff," said the report. For coordination of government-sponsored R&D, the plan proposed to resurrect the interagency Committee on Materials (COMAT). COMAT had been disbanded in the early days of the Carter Administration, then resurrected before Carter left office, and then was again disbanded in the early days of the Reagan Administration.

The President's report had little discussion of the potential for smoothing materials supply problems by developing advanced technologies for more efficient use of materials, recycling, or substitution of abundant materials for scarce ones—themes emphasized in the 1980 Act and its legislative history. While the Administration actually proposed to fund strategic materials R&D at a fairly high level, the President's plan offered few specifics, stating that "favorable tax incentives" in the 1981 tax law would stimulate private R&D of essential materials activity. Any government-financed R&D, the report said, "will concentrate on high-risk, high potential payoff projects with the best chance for wide generic application to materials problems and increased productivity." The exception to this policy was mission-specific projects of the Department of Defense.

Although the President's plan was seen by many as an important first step, its lack of emphasis on materials issues other than those associated with mining and the public lands, as well as the choice of the Cabinet Council on Natural Resources and the Environment to coordinate policy, drew strong criticism from the House Committee on Science and Technology. By mid-August 1982, the Committee had reported a bill—the proposed Critical Materials Act of 1982—to establish a Council on Critical Materials "under and reporting to" the Executive Office of the President. "It is no accident," the Committee report said, "that the Cabinet Council on Natural Resources and Environment, headed by the Secretary of Interior, placed primary emphasis on minerals, mining and related public land policies with almost no attention to basic material processing, conservation, substitution, or new materials development."[83] Only an entity within the Executive Office of the President, the Committee report reasoned, would be able to transcend "normal interagency competiveness and provide the necessary balance in materials policy considerations." The Administration disagreed, arguing that a new layer of bureaucracy would impede—rather than enhance—materials and mineral policy coordination.

Although the bill did not pass in the 97th Congress, the House Science and Technology Committee continued the push for a critical materials council in the 98th Congress. Its Subcommittee on Transportation, Aviation, and Materials held hearings in May and June of 1983, focusing on implementation of the 1980 Materials Act.[84] Administration witnesses, while supporting the need for effective coordination, maintained that the Cabinet Council on Natural Resources and Environment and COMAT would fulfill this need. However, the U.S. General Accounting Office, which had been asked by full Committee Chairman Fuqua to monitor implementation of the 1980 Act, identified several areas in which additional attention would be needed to meet the goals of the 1980 Act, including more effective coordination.[85] While its final report was not released until March 1984,[86] GAO's preliminary findings (as reflected in its testimony) supported the contention of those who held that implementation of the 1980 Act was not adequate.

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[82] *National Materials and Minerals Program Plan and Report to Congress*, submitted by President Reagan, Apr. 5, 1982.

[83] House Report 97-761, Part 1, Aug. 18, 1982, p. 9.

[84] U.S. Congress, House Committee on Science and Technology, Subcommittee on Transportation, Aviation, and Materials, *Hearings on Material Research and Development Policy*, 98th Cong. 1st sess., May 17, 18, 19; June 24, 1983 (Washington, DC: U.S. Government Printing Office, 1984).

GAO pointed out that the Cabinet Council on Natural Resources and the Environment did not include all agencies with important materials responsibilities, such as the Department of Defense and the Federal Emergency Management Agency, which coordinates stockpile planning. COMAT, assigned R&D coordination by the President's plan, had apparently not been involved in determining the need for a major new materials research initiative proposed in the President's budget for fiscal year 1984. The Act called on OSTP to prepare and annually revise an assessment of national material needs related to scientific and technological changes over the next 5 years; while no date was specified for the initial assessment, none had been prepared. Finally GAO noted that the 1980 law did not require the administration to periodically revise and resubmit to Congress its overall materials program plan. Hence, the President's material plan would not necessarily be revised. (Key findings from the GAO report are summarized in box 4-A.)

Another issue taken up at the hearings concerned the potential role of advanced materials in U.S. industrial competitiveness, and in easing import vulnerability. In 1981, Japan had announced a 10-year program giving considerable prominence to advanced ceramics and other "high technology" materials in its industrial goals. Concern had been mounting that U.S. primacy in advanced materials research was in danger of being supplanted as these materials increasingly found commercial application.

By late October 1983, the subcommittee had reported a measure (H.R. 4186) to the full Science and Technology Committee which called for the establishment of a national critical materials council and for increased emphasis on advanced materials R&D. When a Senate-passed arctic research measure that had been endorsed by the Administration was referred to the Committee, it emerged from mark-up with a new Title II, the National Critical Materials Act of 1983. The measure was signed into law by President Reagan on July 31, 1984.

The National Critical Materials Act (Title II of Public Law 98-373) has three major components. First, it establishes a National Critical Materials Council in the Executive Office of the President, to advise the President on materials policy, and define responsibilities and coordinate critical materials policies among Federal agencies. The Council, to be composed of three presidentially appointed members who will need Senate confirmation if they do not already serve in a Senate-confirmed office, is to prepare a report on critical materials inventories, and projected use, including a long-range assessment of prospective critical materials problems.

Second, it calls for the establishment of a national Federal program for advanced materials research and technology, with the Council assuming key responsibilities for overseeing and collaborating with other agencies on the program. The Council is directed to establish a national Federal program plan for advanced materials R&D, and to review authorization and budget requests of all Federal agencies to ensure close coordination with policies determined by the Council. The Office of Management and Budget, in turn, is to consider Federal agency authorization requests in the materials area as an "integrated, coherent, multiagency request" to be reviewed with the

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[85] Ibid., p. 23.

[86] U.S. General Accounting Office, *Implementation of the National Minerals and Materials Policy Needs Better Coordination and Focus*, GAO—RCED-84-63 (Gaithersburg, MD; Mar. 20, 1984).

Council for adherence to the Federal materials program plan then in effect.

Third, the law seeks to promote innovation and improved productivity in basic and advanced materials industries. The Council is to evaluate possible use of centers for industrial technology, authorized by the Stevenson-Wydler Technology Innovation Act of 1980 (Public Law 96-480), as a means to encourage such innovation. It is also called on to establish an "effective mechanism" for efficient and timely dissemination of materials property data.

The Range of Solutions

Thirty years of debate have drawn attention to a very wide range of political responses to materials supply problems. The promise of advanced technologies, both in expanding supply and in promoting more efficient, more flexible use of materials, has received considerably less attention. That is the purpose of this report. Chapters 5, 6, and 7 present in detail the principal subjects of this report—supply alternatives, conservation, and substitution. Chapter 8 discusses policy issues and options related to these subjects.

Box 4-A.—GAO Evaluation of Executive Branch Implementation of the National Materials and Mineral Policy, Research and Development Act of 1980

Soon after passage of the National Materials and Minerals Policy, Research and Development Act of 1980, the U.S. General Accounting Office (GAO) was asked to monitor and review the Administration's implementation of the Act by the Chairman of the House Science and Technology Committee. GAO's final report, issued in April 1984, draws the following conclusions:

- The President assigned overall responsibility for coordination of materials policy to the Cabinet Council on Natural Resources and Environment, but the council has not provided the "continuous decision and policy coordination required" by the Act. The Cabinet Council is restricted to Cabinet members; therefore, representatives from the Federal Emergency Management Agency (FEMA), which oversees stockpile policy, and the Environmental Protection Agency (EPA), which regulates the activities of mining and mineral processing industries, are not included. The Council cannot completely address minerals and materials issues with this lack of membership. In fact, several material-related decisions have been made by independent agencies or individuals with little or no coordination with the Council or sister agencies.
- The President's program plan focused on one of the three policy goals included in the Act—national security. However, almost no attention was given to the Act's other two policy goals—economic wellbeing and industrial production, except to address domestic minerals extraction problems. No consideration was given to the long-term implications of the decline in domestic minerals processing capacity for the U.S. economy and industrial base.
- The Act required the Office of Science and Technology Policy (OSTP) to prepare an assessment of national materials needs related to scientific and technological changes over the next 5 years and to revise such assessment on an annual basis. The Act, however, did not specify a reporting date. Agency officials told GAO that they consider this a low-priority task, and have not prepared the report.
- The Department of Defense was to prepare a report assessing critical materials needs related to national security and to identify steps to meet these needs. This report was to be made available to Congress on October 21, 1981. According to officials in the Defense Department, the report had been sent to the Cabinet Council on Material Resources and Environment in time for it to be used in the preparation of the President's material plan in April 1982. However, the report was still under review within the Administration as of February 1984, and had not been sent to Congress.
- Similarly, the Department of the Interior did not submit a report due to Congress on October 21, 1981, until November 10, 1983. The report was submitted only after the Chairman of a House subcommittee indicated that "legislative action" would be pursued if the report were not submitted. (The Interior report summarizes actions to improve the capacity of the Bureau of Mines to assess international mineral supplies, to increase the level of mining and metallurgical research by the Bureau in critical and strategic minerals, and to improve the availability of mineral data for Federal land use decisionmaking.)
- The only Federal agency to comply consistently with the Act's requirements is the Department of Commerce. (Commerce has completed two materials case studies on critical materials requirements of the steel industry and of the aerospace industry; a third dealing with domestic minerals industries is in progress.)

GAO concluded that the Executive Office should develop an expanded program plan which takes into account Congress' three policy goals of national security, economic well-being, and industrial production. Specific recommendations were:

- The plan should clearly define the terms "strategic" and "critical" to focus attention on those mineral and material markets where the United States is most vulnerable to price increases or supply disruptions and should develop a plan to measure the magnitude of the potential problem in a given market. The benefits and costs of various alternatives such as stockpiling, expanding domestic productive capacity and supply, and developing substitutes should be weighed in this long-term plan which should be geared towards specific minerals or materials.
- The program plan should reach beyond the goal of national security and include issues affecting the law's goals of economic well-being and industrial production, which are now being addressed in an uncoordinated fashion by the Departments of Interior, Commerce, Defense, and others.
- The program plan should address the future role of high technology materials R&D. This alternative should be developed within the report that OSTP is required to prepare under the 1980 Act, and the recommended redirection resulting from COMAT's inventory of Federal material R&D programs.

GAO offered the opportunity for the various agencies to comment on their conclusions and recommendations. The agency responses are as follows:

- The Department of the Interior disagreed on the need to develop an approach to measure U.S. minerals and materials vulnerability. Interior felt it was not necessary to quantify the magnitude or degree of vulnerability in a given nonfuel minerals or materials market.
- The Department of Defense agreed with GAO that the report assessing critical national security materials needs and the steps necessary to meet those needs required by the Act should be made available to Congress. Defense was in agreement with the Department of the Interior regarding measuring U.S. vulnerability.
- The Office of Science and Technology Policy did not comment on the GAO proposal that it prepare the assessment of national materials needs related to scientific and technical changes over the next 5 years as required by the Act. Interior, however, stated that the administration intended that COMAT would constitute the primary means through which OSTP would carry out the Act's reporting requirements. In the opinion of GAO, neither the program plan or COMAT's activities to date assess national materials needs related to scientific and technological changes over the next 5 years; therefore, this requirement has not been met.

CHAPTER 5

Strategic Material Supply

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CHAPTER 5

Strategic Material Supply

Introduction

Strategic material supply vulnerability could be reduced by developing domestic sources of ores and maintaining domestic processing capability or by sufficiently diversifying foreign suppliers to reduce the likelihood that any supply disruption would adversely affect U.S. national security or industrial stability. Prospects for changes in the existing distribution of mineral supply sources depend primarily on whether future demand for various commodities encourages expansion by current suppliers or the opening of new mines in new areas. Other factors include shifts in consumption patterns in the developing nations—e.g., a growth in internal use of resources that result in fewer or higher processed forms of exports—and the decline of production as reserves are depleted. Although market forces and, increasingly, government action in mineral-rich developing countries determine which mineral deposits are chosen for exploitation, neither has contributed or will necessarily contribute to a lessening of vulnerability by promoting either domestic or diversified foreign production.

This chapter discusses the existing lack of diversity of supply and the corresponding lack of adequate domestic supply of the first-tier strategic materials. It also presents an overview of the technology employed in strategic materials supply. (International political factors, which relate to the likelihood of disruptions and their possible durations, are not discussed.) The first section of the chapter considers mining and processing in general and is followed by sections on the specific ore production and processing environments and supply patterns of each of the first-tier strategic materials. The prospects for reduction in vulnerability are assessed. The last section discusses, in terms of U.S. lands and the ocean floor, the possibilities for new mineral finds and improved exploration technology and their effects on expanding the knowledge and availability of strategic materials.

Summary of Supply Prospects

While today's pattern of supply for chromium, cobalt, manganese, and platinum group metals (PGMs) will not change in any appreciable way in the near and, most likely, long-term future, there are some opportunities for direct and targeted government action to diversify foreign sources of these materials away from politically sensitive areas. A concentrated push to diversify foreign sources of supply, however, would inevitably open marginally economic deposits and, in the long run, might do nothing more than simply delay an even greater reliance on the abundant deposits—e.g., those in southern Africa.

Of the first-tier strategic materials, only PGMs are now produced from domestic ores; and in 1982 the amount produced represented less than 1 percent of that year's consumption. Other domestic PGM and some cobalt resources have been under consideration for commercial exploitation. Known chromium and manganese ore resources in the United States are considered improbable candidates for commercial production at any time in the near or long-term future. Without Federal subsidies, production may be possible for larger amounts of PGMs, but is less likely to initiate production of cobalt, and appears unlikely for chromium and manganese even under supply disruption conditions when market prices can rise dramatically. In all cases, only a portion of U.S. needs could be supplied by domestic production. All of these resources, though, represent important in-place stockpiles of strategic materials.

Chromium

Foreign alternatives to the major chromium producers, South Africa and the Soviet Union, are limited in number and in the amount of chromium they could provide. Prospects include the expansion of output from producing deposits in the eastern Mediterranean and the Philippines and the development of laterite and beach sand deposits in the Western Pacific region. These sources might provide an additional 10 to 20 percent of U.S. needs.

Domestic resources could provide up to 50 percent of needs (in a low consumption year such as 1982) for 11 years if four deposits were simultaneously developed at costs about double prevailing rates. One of these deposits, which could supply up to 4 percent of U.S. chromium consumption, has been under recent consideration by a private firm, but production would be contingent upon significant increases in the prices and demand for nickel and cobalt.

Cobalt

If foreign production of cobalt is to diversify, it will most likely result from the opening of cobalt-containing nickel laterite deposits in such countries as New Caledonia and Papua New Guinea, possible expansion of output from the Philippines, and production of cobalt as a byproduct from iron ore mining in Peru.

Four cobalt deposits in the United States could supply up to 10 million pounds annually, if producing simultaneously; this production rate would decline after about 20 years. Private firms investigating three of these properties have suggested that Federal subsidies in the form of price guarantees could assist them in overcoming a prime barrier to production—low and volatile market prices for cobalt. The fourth deposit is not under consideration for production.

Manganese

The greatest opportunities for diversifying the foreign supply of manganese lie in increased production of manganese ore in Australia and Mexico. Mexico's ores require more extensive processing than Australia's and would represent a larger investment to promote increased production. Neither producer will decide to increase production without clear market signals of increasing and sustained demand. Increases from these producers plus Gabon (with transportation improvements) might be able to meet U.S. needs.

The cost of producing ores from known domestic manganese deposits ranges from 2 to 18 times the market price; commercial activity is nonexistent. Simultaneous development of eight domestic deposits could theoretically cover most of U.S. needs over a 10-year period.

Platinum Group Metals

There are no known foreign alternatives to PGMs. South Africa, the Soviet Union, and to a much lesser extent, Canada, will continue to supply the world.

Private development of and production from the Stillwater Complex in Montana appears possible given slight increases in market prices for platinum and palladium and evidence of increased, sustained demand. Initial production would supply about 9 percent of domestic needs, based on 1982 consumption of PGMs.

Exploration

The relatively low economic value of many strategic materials and ample foreign supplies combine to inhibit any domestic commercial exploration for new deposits of these materials. Advances in exploration technology are not specifically directed at finding strategic materials, but general improvements could increase the likelihood of locating deposits, if they exist.

Processing and the Ferroalloy Industry

U.S. ferroalloy production capacity has declined over the last decade. This erosion is expected to continue at a slower pace, resulting in a lean domestic industry that can supply a portion of domestic needs.

Factors Contributing to Change in Supply

It is a consequence of the economics of mining that there are no known "world class" mineral deposits that are not producing. Known deposits that are not producing, whether foreign or domestic, are small in size and/or contain low-grade material. These factors, plus others such as labor and energy costs, accessibility, the effect of perceptions of political risk on investment, and environmental concerns, contribute to these deposits' marginal economic value. Some producing deposits are not considered to be economic by free market standards. The less developed nations that own many of the known deposits consider them such critical sources of jobs and foreign exchange that they are often exploited even if operations must be subsidized.

Mineral activity encompasses a time-consuming, sequential chain of activity: exploration, mine development, ore production and processing, and international trade. Normal changes in supply patterns evolve slowly. Dramatic changes, when they do occur, are the result of perturbations to the system. Two ongoing evolutions in international mineral trade are now affecting mineral supply and the ways in which vulnerability is measured. The first is a shift from export production to domestic consumption. Many producer countries (e.g., Brazil and India) are increasingly using their mineral resources, just as the United States did, as a contribution to their own industrial development. Internal demands for these resources affect the trading relationship these nations maintain with their mineral customers by the reduction of market supplies during high internal growth periods and the dumping of excess supplies on the world markets during recessionary times.

A second and related factor is that producing nations are deciding that it is in their own best interests to promote the export of processed ores rather than raw materials. Since their newer facilities appear to have a competitive edge over traditional processing facilities in industrialized centers, the vulnerability of the West to imported materials is shifting from ores to higher processed forms of strategic materials.

This shift in trade from ores to ferroalloys and from semiprocessed ores to cobalt and PGMs is accompanied by a change in transportation requirements. Ferroalloys contain double to triple the chromium or manganese content of the mined ores, so that shipping the same amount of chromium or manganese as ferroalloys rather than as ores requires less space, fewer ships. While prior processing allows the shipment of a greater amount of chromium or manganese in fewer vessels, PGM and cobalt metal products can be shipped by air at no great increase in cost to the consumer. The growth in cobalt and PGM refining capability in mining countries increases the flexibility of transportation systems (and reduces the overall processing time), resulting in a lowering of the vulnerability of cobalt and PGMs to sea and land transportation problems.

Concern about the vulnerability of transportation routes from producing to consuming nations usually focuses on the problem of open sea lanes in time of war. Consideration must also be given the less dramatic problem of whether land transportation services are and will remain adequate. Mines are often located far inland, in isolated areas. Transportation of ores to a shipping port usually involves an initial overland route (by railroad, truck, aerial tramway). The costs of developing and operating such systems can be a significant factor in the economics of a potential source of minerals. Transportation bottlenecks could prove the most time-consuming aspect of any rapid expansion required in a supply emergency. In addition, land transport is a weak link between producer and consumer in terms of possible terrorist operations.

Technological Advances in Mine Production and Processing[1]

Into the 1990s, the overall picture for mining technology applicable to first-tier strategic material resources should differ only in a few respects from that of today.

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[1] See the following section for a description of various exploration, ore mining, and processing procedures and technologies.

Technology will only marginally enhance the likelihood for domestic production. Changes in technology affect the cost of materials by reducing the capital investment and the unit cost of mining and processing operations. However, low-grade domestic resources of strategic materials are not unique geologically, and any innovations would apply to foreign deposits of higher grades, as well. New technology would not be likely to make domestic sources more competitive. Unless there are discoveries of higher grade ore bodies in the United States or the development of mining and processing technologies that selectively improve the economics of low-grade deposits, marginally economic deposits will remain as such.

If foreign supplies were restricted or unavailable, new technology could provide for domestic production at lower costs than would be possible otherwise. Development costs in open pit and underground mines might be reduced by as much as 15 percent with the use of rapid excavation and continuous material-handling methods and in situ (solution) mining could realize savings of up to 50 percent over today's conventional open pit and underground mine installations. Mine operating costs per unit of material could be reduced by as much as 20 percent in relation to the costs of applying current technologies, with in-situ operation costs perhaps 40 percent below those of conventional methods.[2]

Mechanization of age-old mining methods is the key change now underway in production. Open pit mining, which employs technology to drill, blast, and load rock is expected to use more continuous conveying systems in deeper and steeper pits, and continuous bucket-wheel excavators will come into use. Hard rock underground mining will still be a cyclic operation of drilling, blasting, and loading but there should be increased remote control, rapid conveyor haulage, and mining methods that break rock on remote levels. Machines used to bore shafts (called "raise-boring") will be in general use, but other continuous mining innovations in shaft sinking, tunnel boring, and mining methods will probably be used in only a few mines.

In specific instances, new mining concepts could be applied. Solution mining of manganese deposits is now under investigation and is being conceptualized for other strategic materials. Bioengineering, which uses bacteria in leach treatment of ores, may provide a mining innovation for the future. It is expected, however, only to supplement existing mining and processing techniques.

The low grades of domestic deposits and the attendant costs involved in processing their ores to produce the high-grade industry standard material is a major contributor to their uneconomic status. There are no major changes in processing technologies expected to be available in the future to alter that picture substantially. Domestic cobalt and PGM ores, if in production, are expected to be processed with modifications of today's technologies.

Strategic Material Environments, Mineral Activity, and Technology

Geology of Strategic Materials

Chromium, cobalt, manganese, and platinum group metals are found in greatest concentration in certain classes of rocks (called "mafic" and "ultramafic")[3] which were formed eons ago by solidification from a molten state. Table 5-1 identifies by deposit type and location the major worldwide known deposits of the first-tier materials. The significance of the different deposit types is explained in each of the individual mineral sections below.

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[2] A. Silverman, et al., *Strategic and Critical Mineral Position of the United States With Respect to Chromium, Nickel, Cobalt, Manganese, and Platinum*, contractor report prepared for the Office of Technology Assessment, June 1983.

[3] Rocks that are dominately composed of iron and magnesia silicate (SiO_4) minerals. Ultramafic rocks contain less than 45 percent SiO_2.

A troublesome aspect of any discussion of mineral supply is in establishing agreement over the meaning and use of the basic terms, "resources" and "reserves." Reserves include deposits that were known and were technically and economically feasible to mine at a profit at the time the data was analyzed. Reserves are the only deposits that are immediately available to be developed to meet the need for materials. Resources, on the other hand, include reserves and deposits that are known but are not currently economic to mine, as well as deposits that are merely inferred to exist from geologic evidence. Numbers for both are estimates and should be used only with caution. The Bureau of Mines and the U.S. Geological Survey, which calculate and report the numbers, rely on their own research, the reporting of private data that is often purely voluntary, and data from various publicly available sources. Moreover, the degree of information and commitment to maintaining current estimates of resources and reserves varies greatly among nations. Countries with limited mineral assessment programs may, for instance, not distinguish between resources and reserves, estimate only from operating mines, or fail to conduct economic analyses.

Reserves and resources are often given in terms of ore tonnage. An important qualifier is the "grade" of the desired mineral, the amount of that mineral that is estimated to be contained within the ore. Grades are usually presented in percentages or parts per million (ppm).

Table 5-1.—Deposit Types and Locations of First-Tier Strategic Materials

Chromium:	
Stratiform	South Africa (Bushveld Complex), Zimbabwe (Great Dyke), Finland, Brazil, U.S. (Stillwater Complex)
Podiform	Albania, New Caledonia, Philippines, Turkey, Zimbabwe
Laterite	U.S. (Gasquet Mountain), Philippines, New Caledonia
Cobalt:	
Stratabound	Zaire, Zambia
Laterite	Australia, New Caledonia, Philippines, Cuba
Hypogene	Australia, Botswana, Canada (Sudbury), Soviet Union (Noril'sk), U.S. (Duluth Gabbro)
Hydrothermal	U.S. (Blackbird, Madison)
Manganese:	
Sedimentary	Australia, Brazil, Gabon, India, Mexico, South Africa (Transvaal)
Platinum group metals:	
Stratiform	South Africa (Bushveld), Soviet Union, Canada (Sudbury), U.S. (Stillwater)
Placer	Colombia, U.S. (Goodnews Bay)

SOURCE: Office of Technology Assessment.

Prospecting to Production

Mineral activity[4] can be divided into successive mineral exploration, development, and production phases, all accompanied by ongoing analysis of information accumulated during these phases. The full sequence of activity occurs for only a few projects, as a project will be shelved or abandoned at any stage if the results are not encouraging or if economic conditions become unfavorable. The full sequence, subdivided into six stages, is shown in table 5-2. Although there may be some overlap between stages, they each involve a decision by mining companies or other investors to expend time and resources that grow significantly with each stage. Revenue is not generated until the activity reaches the production phase.

Exploration involves the identification and investigation of target areas with the intent to discover an economic mineral deposit. An analysis of exploration findings of the mineral deposit, combined with a determination of the applicability of mining procedures and capability of ore processing techniques, and marketing studies will determine the initial economic viability of a mineral project. After this

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[4] For more information on this subject, see U.S. Department of Agriculture Forest Service, *Anatomy of a Mine From Prospect to Production*, General Technical Report INT-35, June 1977; and U.S. Congress, Office of Technology Assessment, *Management of Fuel and Nonfuel Minerals in Federal Lands*, OTA-M-88 (Washington DC: U.S. Government Printing Office, April 1979).

Table 5-2.—Mineral Activity

Phase	Stage	Activity
Exploration		
Target identification		
	1.	Regional appraisal
	2.	Reconnaissance of region
Target investigation		
	3.	Detailed surface investigation and chemical analysis of samples
	4.	Detailed 3-dimensional analysis of site by drilling, testing of samples. Project feasibility studies
Development	5.	Drilling to block out deposit. Construction of mine workings, ore processing plants, support facilities
Production	6.	Operation of mine, ore processing, and shipment of material to market

SOURCE: U.S. Congress, Office of Technology Assessment, *Management of Fuel and Nonfuel Minerals in Federal Lands*, (Washington, DC: U.S. Government Printing Office, April 1979), p. 47.

determination has been made, *development* work proceeds to bring a deposit to the point of *production*—the actual mining, ore processing, and shipment of material to market.

During target identification (stages 1 and 2), a large area is surveyed to locate areas of promise. Research is based largely on previously collected industry and government data and geologic theory and is supplemented by field inspection by air or on the ground.[5] Successful conclusion is marked by a decision, usually made by the exploration experts, to focus on particular areas of high potential.

The objective of target investigation (stages 3 and 4) is to locate a deposit of a desired mineral that has potential for commercial exploitation. This involves the gathering of data from the region selected during the previous stages and proceeding with sampling and mapping of geologic features, geophysical surveys (usually conducted from the air), limited drilling to determine the nature of the layers below the surface, and laboratory analysis of samples obtained in the region. If a promising deposit is found during stage 3, then a decision is made as to whether the potential of the deposit justifies the expenditure of further funds for stage 4. If so, a process begins to define the grade and extent of the deposit and to determine the detailed composition of the minerals in the deposit. It is at this stage that sufficient information is obtained to determine whether the deposit is of commercial value and whether development activities are advisable. Three-dimensional mapping of the deposit, with drilling samples taken at close intervals, provide detailed maps of the ore and the surrounding rock. This information and analysis of mineral content of the ore are used to develop mine plans. Samples are used to test prospective ore processing systems. In addition to providing the information for the design of the mine and the ore processing plants, feasibility studies during this stage provide the basis for the final company decision to commit funds to a mining project and provide investment groups with the information they need to justify loans for or equity involvement in a project.

Mineral activity then moves into the development stage during which the mine and ore processing plant are constructed and transportation and other support facilities are installed. This stage is the greatest expense of the mineral activity process. Once the final production stage commences, it continues for as long as the project can produce on commercial terms. Should economic conditions change, perhaps due to depressed market prices or depletion of high-quality ore, the facilities are closed either temporarily ("placed on care and maintenance") or permanently. In addition, the mining industry is quite accustomed to delaying partially completed projects when market conditions change. There can be a considerable time gap between the end of the exploration and the beginning of the development stages.

This process of mineral activity is long-term, risky, and expensive. In general, each successive stage is more expensive and takes more time than prior stages. The costs and time involved vary and are dependent on a number of factors. For instance, both will increase if a deposit is buried rather than exposed on the surface. In 1977, according to an earlier OTA report,[6] estimates of average U.S. exploration costs per mineral project ranged from $1.7 million to $5.4 million and took up to 5 years to complete; mine development costs varied from millions to several hundred millions of dollars with times ranging from less than 1 up to 13 years. A 1980 report[7] stated that major international mining projects take at least 7 to 8 years after the time of discovery and often cost up to $1 billion to reach the production stage. Once production begins, mining ventures may need years of continuous operation to show an adequate return on the capital investment.

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[5] Remote sensing (exploration by satellite), while it has not yet located ore deposits, is a tool which provides basic scientific data which can be coordinated with geologic concepts to assist in the process.

Exploration Technology

The geologist's search for a specific mineral is aided by knowledge of the environment in which it is likely to be found. Thus, expected host rock, trace metal, and gangue[8] mineral associations, wall rock alteration occurrences, and the age of a mineralization can all be keys to discovery. Exploration technologies which help to identify these environments as well as the mineral itself include three types: visual, geophysical, and geochemical. Visual methods are the oldest, simply being the surveying of an area for geologic formations and features known to be favorable to the desired minerals. Such methods are still used in the first stage of mineral activity in the search for regions deserving of more detailed study.

Technology has now taken the explorer beyond the powers of eyesight to advanced geophysical methods. Physical properties of mineral formations such as density, magnetic behavior, electrical conductivity, and radioactivity provide characteristic patterns which can be used for identification. Some of these measurements are taken on the ground, some "down hole" and others can be conducted by air. Geochemistry involves trace metal analysis of air, water, soil, and rock materials in the region of mineral exploration.

Mining Technology

The mining method selected for a particular project will vary according to the size, type, and position of the deposit; the grade of the ore, its strength and the strength of the surrounding waste rock; and the unit value of the desired mineral.

There are two general classes of mineral deposit: surface and vein. Vein deposits are formed by the deposition of minerals by molten rock as it moves upward from deep below the surface through cracks in the surface rock. As the molten rock cools, the contained metals (under the action of pressure and heat) can concentrate in particular locations to form veins of minerals. Although some vein deposits may be accessible by removing the surface rock, generally such deposits must be mined by underground methods.

Surface deposits are found at or near the surface. Some, known as placer deposits, occur as concentrations of mineral or metal particles that have washed away from an exposed deposit to mix with sand and gravel in river beds or ocean beaches. (Placer deposits have been an important source of PGMs and gold.) The metals are recovered by dredging river beds or beaches and using flowing water and gravity to separate the heavier precious metals from the lighter sand and gravel.

Another important class of surface deposit is formed by the weathering of surface rock that contains dispersed metals such as nickel and chromium. Through a continual process of changing temperatures and rainfall, these metals are washed to lower levels of the rock formation where they concentrate in amounts that are attractive for commercial exploitation. (Deposits of nickel, known as nickel laterites, are formed in this way. Such deposits may also contain concentrations of chromite, the mineral from which chromium is obtained.) Laterite deposits are generally mined from the surface by open pit methods.

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[6] *Management of Fuel and Nonfuel Minerals in Federal Lands*, op. cit.

[7] The Brandt Commission, *North-South: A Program for Survival* (London: Pam Books, 1980), p. 156.

[8] Gangue is that part of an ore body which contains the undesirable minerals—i.e., waste material.

Mining processes thus fall into two general classifications: underground and surface mining. In underground mines a complex system of shafts are sunk and tunnels bored which selectively follow the ore veins or pockets of minerals with highest grade material. Blasting techniques must be used to remove the ore, which is often crushed within the mine prior to hauling above ground. Underground mining methods (called "stoping" by American miners) are age old and highly varied. They include open stoping (room and pillar, for instance, is a form of open stoping), shrinkage, cut and fill, and square-set stoping and block caving. Today, underground mining is becoming increasingly mechanized in order to improve productivity.

Placer and open pits are surface mining techniques, both of which take advantage of large and efficient earthmoving machinery. In dredging operations, a form of placer mining, the gravel containing minerals is scooped up by bucket lines or a dragline onto a floating plant which separates the gravel into a mineral concentrate and tailings (waste product). In an open pit mine access to the ore body is accomplished by removal of the waste overburden (upper layer of earth lacking in economic concentration of metals). The material in the ore body is then removed, as the pit is formed, top to bottom by sequentially blasting (in hard rock[9] mines) and then mechanically loaded into equipment for hauling up out of the pit for processing. A choice whether to use open pit or underground mining methods is based, in part, on the cost of removing the overburden and whether the waste rock can sustain the sloping sides of the pit.

Solution mining techniques are now used for extracting soluble materials such as potash and salt in situations where conventional mining methods would not be economic. There are two general versions. In the first, "heap leaching," ores are mined and spread on the surface. A solvent is then applied and the resultant solution of minerals is collected and processed. The second version—"in situ leaching"—involves the introduction of the solvent into the orebody in place, followed by pumping out of the resultant mineral solution. The application of in situ leaching in hard-rock mining requires an initial fracturing of an ore body before leaching solvents can effectively produce a solution of the desired minerals to be extracted from the ground. These techniques for hard-rock mining are under active research but have not yet been attempted on any virgin deposits. They may offer a possible solution to the problem of the poor economics of low-grade domestic deposits if they can reduce the overall recovery costs of producing a high-grade material. Research areas include equipment, solvents, technologies for fracturing ore bodies in place and for controlling the movements of fluids through them.

Bioengineering may provide mining with a technique to recover metals from ores too low in grade to process conventionally or from existing tailings dumps.[10] Certain bacteria will liberate and concentrate small grades of metals, and natural bacterial leaching is used currently to recover copper and uranium from sulfide deposits. A major drawback of bacterial leaching is the slow rate of the process compared with chemical extraction. The hope is that genetic manipulation can enhance the natural leaching properties of bacteria.

Potential for Change in the Supply of Strategic Materials

Once a mineral activity moves into the development stage, its details are generally widely known. Given the time-consuming development process, it is not difficult to project world ore production (a total of existing and developing new sources) at least a decade into the future. Even beyond 10 years, potential new sources can be readily identified because there are only a limited number of known deposits, undergoing investigation, that could be opened or expanded to capture a share of the ore market. Discoveries of major, new deposits are possible but unpredictable. Thus, projections of production beyond about 20 years become unreliable.

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[9] Hard rock refers to material that has a strong bonded structure and must be excavated by using blasting techniques in which an explosive charge is placed in a hole bored in the rock and detonated. Most first-tier strategic materials are mined from hard-rock ore bodies.

[10] See U.S. Congress, Office of Technology Assessment, *Commercial Biotechnology: An International Analysis*, OTA-B-218 (Washington DC: U.S. Government Printing Office, January 1984), pp. 226-228; Joann Dennett, "Microbe Miners," *AMM Magazine*, July 2, 1984; and Joseph Alper, "Bioengineers Are Off to the Mines," *High Technology*, April 1984.

Any change in the existing mine production of strategic materials will be determined by market demand and by the efforts of mineral producer governments to provide employment for their citizens, obtain foreign currency, and promote industrial development. Extraordinary conditions, such as a prolonged supply disruption of a substantial portion of any one mineral, could also encourage increased production from existing or the development of new sources of supply.

Table 5-3 presents a summary of the supply prospects of the first-tier strategic materials, a picture of the geographic distribution of the United States' major sources of the first-tier strategic materials along with the relative present and estimated future contribution of the producers. (The ranking system is based on the magnitude of each producer's output combined with the extent of its participation in Western trade.) The table also identifies the major barriers to expansion of production and initiation of new sources of supply.

Constraints include limited knowledge about the extent of the resource base; the equipment and skilled labor needs to mine, process, and refine the ores; and the limits of support systems such as energy sources and transportation facilities. Direct economic constraints include the need for massive capital to finance development work and uncertainty about future markets. Political risk (contractural instability, threat of nationalization without compensation, uncertainty over guarantees of sufficient mine life to attain expected rate of return) is a component of the economic analysis of any mining project located in a developing country.

Available mine capacity for chromium, cobalt, manganese, and PGMs has been highly underused in the early 1980s, the effect of several years of worldwide economic recession. While the fortunes of the mining industry have historically been cyclical, the recent sustained oversupply and low prices have adversely affected new investment in these commodities. Although some new mining ventures for these materials are being evaluated, few are going forward. It is expected that any increase in demand in the near future will be supplied by current mines operating at capacity and the reopening of recently shut mines.

Even under healthy market conditions, the ample reserves and resources of the South African mines for chromite, manganese, and PGMs and of the Zairian/Zambian mines for cobalt serve as impediments to investment in the development of new mining areas. All new ventures must compete for markets against the strength of the existing producers and their ability to increase production easily to meet any new market demands.

The immediate response capability of existing producers to a supply disruption depends on the status of mining at the time and the corresponding extent of development needed. For instance, during such periods as the early 1980s, when mining operations generally were operating at as little as 50 percent of capacity, an expansion to full capacity could be simply a matter of hiring personnel for more shifts in a mine or for reopening mines. This could be done in a matter of weeks, or at most, in a few months. On the other hand, a mine already operating at full or close-to-full capacity during a tight market would require substantially more time to expand production, even though the plans for expansion would be available. Any producing mine is continually upgrading its reserves and blocking out future production areas to open, given a change in market conditions. In an underground mine, however, new shafts might have to be prepared by extensive blasting and boring, a time-consuming process. An open-pit mining operation with simple ore concentrating equipment can increase output much more rapidly by adding blasting and hauling equipment. Ultimately, however, limitations could be imposed by avail-

Table 5-3.—First-Tier Strategic Materials Supply Prospects

Regions	Minerals	Country producers[a]	Importance[b]		Primary constraints to increased availability[c]
			Now	Potential	
North America	Chromium	NA			
	Cobalt	CANADA	2	2	nickel demand, refinery limits
		United States	—	3	high cost deposits, demand for various primary metals
	Manganese	MEXICO	3	2	customer acceptance of quality
	PGM	CANADA	3	3	nickel/copper demand, refinery limits
		United States	—	3	demand for PGMs, competition
South America	Chromium	NA			
	Cobalt	Peru	—	2	processing facilities
	Manganese	BRAZIL	2	2-3	local demand
	PGM	NA			
Australia and Oceania	Chromium	PHILIPPINES	2	2	infrastructure
		Pacific rim	—	3	proof of feasibility
	Cobalt	PHILIPPINES	2	2	demand for nickel
		AUSTRALIA	2	2	demand for nickel
		New Caledonia	—	3	demand for nickel
		Papua New Guinea	—	2	demand for cobalt/chromium
	Manganese	AUSTRALIA	2	1-2	hauling equipment
	PGM	Pacific rim	—	?	proof of feasibility
Eurasia	Chromium	FINLAND	3	3	possible resource limits
		ALBANIA	2	1-2	unknown
		GREECE	3	3	resource limits
		TURKEY	3	3	improved knowledge of resources and technology
		INDIA	3	3	resource limits, infrastructure, local demand
	Cobalt	FINLAND	2-3	2-3	possible resource limits
	Manganese	INDIA	3	3	resource limits, infrastructure, local demand
	PGM	NA			
Africa	Chromium	SOUTH AFRICA	1	1	transportation
		ZIMBABWE	2	1	transportation
		MADAGASCAR	3	2-3	seasonal operation, infrastructure
	Cobalt	ZAIRE	1	1	processing, refinery limits
		ZAMBIA	1	1	processing, refinery limits
		Morocco	—	3	resource evaluation
		BOTSWANA	3	2-3	transportation
	Manganese	SOUTH AFRICA	1	1	transportation
		GABON	2	2	transportation
	PGM	SOUTH AFRICA	1	1	refinery limits
Eastern Bloc	Chromium	SOVIET UNION	2	2-3	unknown
	Cobalt	SOVIET UNION	3	3	unknown
		CUBA	3	2	unknown
	Manganese	SOVIET UNION	3	3	unknown
	PGM	SOVIET UNION	1	1	unknown

NA—Not applicable.

[a] UPPERCASE indicates a current producer.

[b] Key: 1 = major
2= medium
3 = minor
? = unknown
Based on assessment of relative production levels and contributions to Western trade.

[c] Any expansion/development would require capital investment, to a varying degree, in mining, processing, and refining infrastructure.

SOURCE: Office of Technology Assessment, 1984.

able processing facilities, such as smelting and refining operations.

Processing of Strategic Materials

Once removed from the ground, all ores undergo some level of processing. Technologies chosen will be based on the extent of processing required due to the condition of the ore (e.g., the amount of upgrading necessary to produce a salable product and the level of difficulty involved in separating out the unwanted minerals) and the intended end use of the mineral.

At the mine site, preliminary processing will take place in order to separate the desired minerals from the unwanted rock (gangue) that accompanies them, thereby, increasing the grade and value of the sought-after mineral. These "beneficiation" techniques to produce "ore concentrates" include simple hand-sorting, mechanical crushing, and gravity concentration methods. A more sophisticated and widely used method is flotation. Crushed ore is passed through vats of water containing reagents which make one or more of the ore minerals water repellent. These particles attach to air bubbles and float to the top of the vats where they can be selectively removed.

Even after the minerals are concentrated, further processing steps are required to alter their form. Manganese carbonate minerals, for instance, must be heated to convert them into manganese oxides. Manganese oxides and chromite (chromium ores) are smelted into ferroalloys.[11] Cobalt and PGMs, once in metal form, must be highly purified before they are useful for certain applications. Finally, metal alloys such as stainless steels and superalloys are manufactured from ferroalloys or relatively pure metals and used in applications such as hubcaps and jet engines.[12]

This multistep processing of ores into useful forms of metals takes a variety of paths; the appropriate choice depends on the nature of the ore and the type of product desired. Processing facilities are often tailored to a particular ore body or type, production rate, and metal production. Other than the initial beneficiation steps, processing does not necessarily take place at the mine site. However, there is an increasing tendency to combine mine production and downstream processing of minerals. This tendency and the consequences to U.S. import vulnerability is discussed more fully below and in the appropriate mineral sections which follow.

Processing Technology

Extractive metallurgy involves the recovery of metals and metal compounds from ores and mineral concentrates. Either a pyrometallurgical or hydrometallurgical method is used, followed in some cases by an electrolytic refining process.

In pyrometallurgy, heat is used to melt the concentrate and, in some cases, to promote a chemical reaction that will change the ore mineral into an alternate chemical compound. Metals are separated out in gaseous form, collected as they rise from the "melt" or in their liquid state, by differences in densities. Smelting—the technique used to produce ferroalloys—is a pyrometallurgical process.

Hydrometallurgy is chemical processing in which metals are selectively leached (dissolved) from ores and concentrates. The variety of minerals to be separated determines whether an acid or alkaline solvent is applied. Hydrometallurgical processes are increasingly selected over pyrometallurgical processes because they use considerably less energy and produce less air pollution.

In an electrolytic process, a metal is "won" (separated out) from a solution and deposited on a cathode (the negative side of an electrical flow) in a relatively pure form.

No technology ever completely recovers all the desired metal contained in the ores in which they are found. Recovery rates (the amount of contained metal that is liberated) can range from about 25 to 95 percent and depend on both the physical limits of the processing methodology and value attached to each specific metal in an ore body.

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[11] Ferroalloys, alloys of iron, contain a sufficient amount of one or more other chemical elements (in this case, chromium or manganese metal) to be used as an agent for introducing these elements into molten metal, usually steel. Ferroalloys are produced by smelting ores in electric arc furnaces. See the chromium and manganese sections that follow for more discussion on processing.

[12] For a discussion of metal processing, such as steelmaking, see U.S. Congress, Office of Technology Assessment, *Technology and Steel Industry Competitiveness*, OTA-M-122 (Washington, DC: U.S. Government Printing Office, June 1980).

Production and Processing of the First-Tier Materials

The United States is not a producer of chromium, cobalt, manganese, or PGM[13] ores, although this has not always been the case. At some stage, however, domestic plants still enter the processing chain of such ores.

The worldwide chromium industry is characterized by a large number and variety—big and small, public and private sector—of ore producer firms. Chromite deposits also vary widely in size and are mined by underground and surface methods and concentration methods range all the way from simple manual sorting to flotation systems.

Manganese deposits are fewer in number and the producing industry is more concentrated than that for chromium. The deposits are generally abundant and can be relatively easily expanded in bulk terms. Often their expansion capabilities are restricted by equipment and transportation systems, rather than the size of their reserves. The majority of the world's producing manganese deposits are oxide, rather than carbonate minerals, and are mostly mined by surface methods. Oxide ores need only to be concentrated; while carbonate ores must be reacted with oxygen to form manganese oxide compounds prior to the ferroalloy stage of processing.

Most of the chromium and manganese mined is consumed by the steel industry. Manganese is a processing agent, and both are used as alloying agents. Producers of these ores have traditionally engaged in the initial processing of the ores they mine—sorting and concentrating them by grades of mineral, chemical content, and physical condition—and leaving the downstream processing to the steel industry. World trade in both chromium and manganese, however, has been shifting in the past decade from concentrated ores to ferroalloys.

The growing ferroalloy production capacity of ore producers (and the steel industries of developing nations) competes with rather than supplements traditional ferroalloy plants in the United States, Western Europe, and Japan. Important factors identified as contributing to this shift are lower labor and energy production costs and lower transportation costs for higher metal content ferroalloys. It is not clear whether the competitive edge of new producers of ferroalloys is due to free market economics or whether government subsidies have promoted economically unsound competitors. In any case, as ore producer countries receive the benefits of exporting a higher value product, the shift in production away from the industrialized West is forcing adjustments (due to unemployment from plant closings, and reduced availability of capital for modernization which further diminishes competitiveness) and resulting in a reduction in U.S. ferroalloy production capability.

It is not clear whether trend toward the importation of higher processed material increases the import vulnerability of the United States. At the same time this processing shift is occurring, Western Europe and the United States are importing increasing amounts of final steel products from ore producer nations and others, and their needs for raw and semiprocessed forms of chromium and manganese are decreasing. It is true that, as integration increases in ore-producing countries, system dependencies increase—i.e, concern now must include not only the assurance that a foreign mine will continue to produce and concentrate ores, but also maintain the operation of a smelting plant. Lack of adequate domestic ferroalloy processing capacity could complicate and add considerably to the costs involved in efforts to cope with any emergency ore supply disruption and would probably increase the response time to an emergency. On the other hand, the higher value of processed ores means that an overt act of a supply interruption becomes more costly to producers and a growing number of processors and might affect such an event's likelihood. In addition, processed ores contain higher amounts of metal per unit volume than ore concentrates and therefore larger amounts can be transported at a time. It is economically feasible to airship refined cobalt and PGMs and avoid supply disruptions caused by surface transport interdictions. Ferroalloys, like ore concentrates, are still confined to ocean shipment due to their weight and volume.

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[13] Current domestic production of PGMs evolves from the refining of copper ores.

Cobalt is only a secondary product of any current mining operation, therefore, its supply is tied to the demand for the nickel and copper with which it usually occurs. The ore producers control a substantial amount, but not all, of the downstream processing of cobalt. PGMs are primary products, coproducts, or byproducts; and the industry is highly concentrated and is expected to remain so. Almost the entire downstream processing of PGM ores is controlled by the ore producers. As cobalt and PGMs often occur in the same ore bodies, their processing paths are often the same.

Cobalt and PGMs are consumed in metal or chemical form. The ores for both materials usually contain a variety of metals in either oxide or sulfide forms, and their processing paths are complex and tailored to the mineral content of the individual mines. The United States has always had a limited ability to process cobalt and PGM ores, relying instead on importing these materials in their usable forms. (An increasing interest in recycling catalytic converters, however, is promoting the development of domestic refining capacity for platinum that may be usable for virgin PGM ores.) Europe, the first consumer of these metals, was also the home of companies that controlled most mining operations during the colonial era; semiprocessed forms of the ore were physically transferred from the ore-producing countries to northern Europe for the final refining processes. This flow still occurs, but mining countries are gradually developing refining capability. This new capacity does not yet appear to be replacing the existing refining capacity, but is absorbing growth in demand. Meanwhile, more diversified sources of refined cobalt and PGM products are being created and the overall time required to process the ores and produce the metal forms is being shortened.

Chromium Production and Processing

The chromite industry is concentrated in the Eastern Hemisphere and includes a large number and variety of firms—big and small, public and private sector. These producers are now shifting from simply mining and trading chromium ore to producing and trading ferrochromium as well.

The only mineral form of chromium ore is chromite. Most of the chromite resources of the world occur in stratiform deposits—layered, long continuous seams that are often visible on the surface. Podiforms are the second major geologic deposit type for chromite. They are small in comparison with stratiform deposits and are discrete, lens-shaped, and usually undetectable without the use of sophisticated exploration tools unless a portion of the deposit happens to appear on the surface. Lesser deposits of chromite are found in laterite formations and alluvial (placer) deposits. Laterites are principally found in tropic or warm temperate zones and are not exploited today as a source of chromite due to general low grades of contained chromite and its granular form.

Any analysis of chromium production is complicated by the multiplicity of ways in which the commodity is reported: chromite, chromite concentrates, contained chromic oxide or chromium, recovered chromic oxide or chromium, etc. Chromite is primarily iron, chromium and aluminum oxides with varying amounts of silica and magnesium.[14] Chromite ore is usually defined in terms of its chromic oxide (Cr_2O_3) content (rarely more than 50 percent), as well as its chromium-to-iron ratio and aluminum oxide content. Once mined, chromite is usually concentrated to increase its chromic oxide (or, chromium) content. These "chromite concentrates" are sold, in part, on the basis of their chromic oxide content. The chromium content of chromic oxide is 68 percent by weight, and the Bureau of Mines defines its chromite data as 22 to 38 percent contained chromium.[15] Throughout the following discussion, an attempt has been made—wherever possible—to convert data into *chromium* units so that comparisons can easily be made by the reader. In addition, the reader should note that the chromium contained in chromite ores and concentrates ("chromium content") is greater than that which will ever be extracted from the ores by any metallurgical process. Thus, "recovered chromium" is the true estimate of the amount that would be available for use.

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[14] Naturally occurring chromite is a combination of minerals described by the chemical formula $(Fe,Mg)O \bullet (Cr,Al,Fe)_2O_3$.

Each chromite mine differs in the type of product it offers: the ore grade and its chemical composition and physical characteristics. Historically, the ores have been classified into three groups, reflecting primary end uses: "metallurgical" (minimum 46 percent chromic oxide with a chromium-to-iron ratio greater than 2:1), "chemical" (40 to 46 percent chromic oxide and chromium-to-iron ratio of 1.5:1), and "refractory" (high aluminum content). Other considerations affecting end use feasibility of various ores are their other chemical characteristics (e.g., silica content) and physical characteristics (e.g., size and condition). South African ores are of both refractory and chemical grades, and tend to be friable (i.e., break up easily). The Philippine deposits are principally refractory grade, but its ores are used for other applications by blending. Turkey's and Zimbabwe's deposits primarily provide metallurgical ores.

The distinction between chemical and metallurgical grades has become less important due to the adoption of the argon-oxygen-decarburization (AOD) process for producing stainless steel. This process allows the use of high-carbon ferrochromium (made from chemical ores) rather than low-carbon ferrochromium (from metallurgical ores) and has boosted the importance of the South African deposits at the expense of higher priced metallurgical ores from Zimbabwe and Turkey.

Foreign sources supply all of the U.S. requirements for chromite (there has been no domestic mine production since 1961) and supply an increasing share of its ferrochromium needs at the expense of the domestic ferroalloy industry. In 1971 the United States obtained 87 percent of its chromium imports in the form of chromite and 12 percent in the form of ferrochromium; by 1981, the imports were roughly equal.[16] Because no Western Hemisphere ore producer supplies chromite or ferrochromium in substantial quantities to the United States, most imports must transit the Atlantic or Pacific Oceans.

While 19 countries contributed to the production of chromite in 1982, almost 75 percent of the world's total was provided by South Africa, Zimbabwe, the Soviet Union, and Albania. Table 5-4 lists 12 major producers and their reserves and production for 1982. South Africa is the principal source of ore for the United States, Western Europe, and Japan. Other major suppliers to the United States are the Soviet Union, the Philippines, and Albania. Turkish and Greek ores are shipped primarily to Western Europe. France is Madagascar's major customer. Brazil, the only substantial Western Hemisphere producer, exports mainly to Japan.

The Soviet Union long played a significant role as chromite supplier to the world. In the mid-1970s, however, its exports to areas outside the Eastern bloc began to decline, until by 1982 they were a fraction of those a decade earlier. Decreasing reserves, increased costs of production, and political control over export policies are the major reasons that have been suggested for this change.

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[15] U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries*, 1984.

[16] U.S. Department of the Interior, Bureau of Mines; *Mineral Commodity Profiles 1983: Chromium*, p. 4.

Table 5-4.—World Chromite Reserves and Production by Country (thousand short tons, gross weight)[a]

Producer country	Reserves 1981	Production 1982	Percent of world production
Albania	2,000	1,320	12
Brazil	9,000	1,050	10
Finland	19,000	440	4
Greece	1,000	46	<1
India	15,000	375	3
Madagascar	230	100	1
New Caledonia	2,000	25	<1
Philippines	23,000	390	4
South Africa	910,000	2,385	22
Turkey	5,000	410	4
Soviet Union	17,000	3,750	34
Zimbabwe	19,000	470	4
Other		146	1
Total	1,000,000	10,907	100

[a] Chromite typically contains from 22 to 38 percent chromium.

SOURCE: Reserves—Bureau of Mines, *Mineral Commodity Profile 1983: Chromium*, table 3, p. 8.
Production—Bureau of Mines, *Minerals Yearbook 1982*, table 14, p. 213.

Producer countries currently export between 35 and 100 percent of their chromite as ores with ferrochromium production taking an increasing share for consumption by local steel industries, as well as export. From South Africa, exports of chromite ore, as opposed to ferroalloys, were 76 percent of production in 1969 and only 35 percent in 1980. South Africa is now the major supplier of ferrochromium to the free world market and provided 49 percent of U.S. imports in 1982. Of the ore producers listed in table 5-4, only Madagascar and New Caledonia have not yet developed ferrochromium production capability. The majority of Zimbabwe's ores are now converted to ferrochromium before export to the United States, Europe, and Japan. In 1982, Yugoslavia—which must import most of its chromite feed—supplied 11 percent of the United States' ferrochromium imports, placing it a distant second to South Africa. Soviet exports of ferrochromium products, like those of ores, are primarily to the Soviet bloc countries.

Extending this vertical integration trend, several South African firms and one Finnish firm now mine ores, process ferrochromium, and produce stainless steel. Greece's recent ore expansion and ferrochromium plant development is aimed at achieving a similar vertically integrated industry. Table 5-5 shows how the ferrochromium industry has shifted over 6 years between 1974 and 1980. For the most part, the traditional centers of ferroalloy production in the industrialized West have declined in total output and have lost market shares to vertically integrated ore producers.

Foreign Production of Chromium

In market economy countries, as shown in table 5-6, chromite production is spread among many private and some public sector firms. Central economy countries (the Soviet Union, Albania, and Madagascar) operate their mines and market production through a central agency. In South Africa, Turkey, and Zimbabwe there is considerable multinational firm involvement. South Africa's ore is produced by 10 companies, operating some 20 mines along parallel seams in the Bushveld Complex. The combined production of Transvaal Mining, Transvaal Consolidated, and Samancor dominates South African output, and the majority interest in these firms is held by four of the six local investment houses ("groups"). U.S. firms engaged in South African chromite mining are Union Carbide, Metallurg, and International Mineral & Chemical. Great Britain is represented in South Africa by investors with long-term interests in the group houses, while West Germany's Bayer Group owns and operates one mine. Eighty percent of Zimbabwe's out-

Table 5-5.—Ferrochromium Production by Country (thousand tonnes, gross weight)

Country[a]	1974	Percent of total	1980	Percent of total	Percent change 1974-80
BRAZIL	38.1	2.0	93.4	3.2	145
FINLAND	48.1	2.6	49.9	1.7	4
France	111.6	6.0	86.2	2.9	−23
INDIA	15.5	0.8	16.3	0.6	5
Italy	39.9	2.1	40.8	1.4	2
JAPAN	541.6	29.1	427.3	14.4	−21
Norway	30.8	1.7	11.8	0.4	−62
SOUTH AFRICA	193.2	10.4	565.2	19.1	193
Spain	20.9	1.1	19.1	0.6	−9
Sweden	100.7	5.4	188.7	6.4	87
United States	305.7	16.4	216.8	7.3	−29
SOVIET UNION	184.1	9.9	698.5	23.6	279
YUGOSLAVIA	39.0	2.1	64.4	2.2	65
ZIMBABWE	181.4	9.7	199.6	6.7	10
Other[b]	12.0	0.6	282.2	9.5	2,252
Total	1,862.5	100.0	2,960.2	100.0	59

[a] Upper case indicates country was ore producer in both years, but did not necessarily cover its needs.
[b] In 1980: ALBANIA, Czechoslovakia, East Germany, West Germany, PHILIPPINES, Poland, and TURKEY.

SOURCE: Charles River Associates *Processing Capacity for Critical Materials*, OTA contract report, January 1984.

Table 5-6.—Chromite Mining Industry by Country

		Ownership		
Country	Major firms	Sector	Major holders[a]	Primary national identity
Brazil	Cia. de Ferro-Ligas da Bahia S.A. (Ferbasa)	Private	Various	Local
Finland	Outokumpu Oy	Government	(81)	Local
		Private	(balance)	Local
Greece	Hellenic Ferroalloys S.A.	Private and government	Hellenic Industrial Mining & Investment (HIMIC) (96)	Local
India	Various	Private and government		Local
Madagascar	Kraoma	Government	(100)	Local
New Caledonia	Societe de la Tiebaghi	Private	Inco (55)	Canada/U.S.
			Various	French
Philippines	Acoje Mining Co.	Private		Local
	Consolidated Mines Inc.[b]	Private		Local
	Trident Mining & Industry Corp.	Private	[c]	Local
	Philchrome	Private	Kawasaki (15)	Japan
South Africa[d]	Transvaal Mining and Finance	Private	Gencor (100)	Local
	Transvaal Consolidated Land and Exploration	Private	Barlow Rand	Local
	UCAR Chrome Co.	Private	Union Carbide	U.S.
	Cromore Ltd. & Bathlako Mining Ltd.	Private	Samancor[e] (100)	Local
	Waterkloof Chrome Mines	Private	Metallurg	U.S.
	Chrome Chemical S.A.	Private	Bayer Group	W. Germany
	Lavino S.A., Ltd.	Private	International Minerals & Chemical Corp. (100)	U.S.
Turkey	Etibank	Government	(100)	Local
	Egemetal Madencilik A.S.	Private	Metallgeselischaft	W. Germany
	Turk Maadin Sirketi	Private	Metallurg	U.S.
Zimbabwe	Zimbabwe Mining & Smelting	Private	Union Carbide (100)	U.S.

[a] With approximate percentage of control, if available.
[b] Operated by Benquet Corp. (local Philippine firm).
[c] A U.S. firm invested in Trident's operation in 1984.
[d] There are six finance houses (the "Groups") which dominate the South African industry: The Anglo American Corp. of S.A. Ltd. (AngloAmer); Gold Fields of S.A. Ltd.; General Mining Union Corp. Ltd. (Gencor); Rand Mines/Barlow Rand; Johannesburg Consolidated Investment Co. Ltd. (JCI); and Anglo-Transvaal Consolidated Investment Co. Ltd. (AngloTC).
[e] Samancor is owned by Gencor, Anglo American, and Iscor, which is a state-owned, integrated steel corporation.

SOURCES: E&MJ 1983 *International Directory of Mining;* Bureau of Mines, *Mineral Commodity Profile 1983: Chromium*; Office of Technology Assessment.

put is generated from two mines east of the Great Dyke deposit by a firm owned by Union Carbide. Albania's government operates more than a dozen mines located in four areas along its eastern border with Greece and Yugoslavia.

Among the middle-level producers, Turkey has three major firms with eight mines, along with numerous smaller (many one-person) operations. Half of Turkey's output, however, comes from mines operated by a state-owned firm. U.S. (Metallurg) and West German (Metallgesellschaft) firms are involved in the other two important Turkish ventures. There are 125 chromite deposits scattered among the islands of the Philippines, but only 12 mines were operating in 1980. The majority of these are locally owned and operated; two are considered major producers. (Japan's Kawasaki Steel has a minority interest in a recently initiated beach sand operation on Palawan Island in the Philippines. An American firm operates the mine for Kawasaki.) Madagascar's government firm has two open pit mines, one of which is a primitive operation accessible only in the dry season. Finland's government-controlled firm produces from a mine along a stratiform deposit. Greece has one major, primarily government-owned operation. Three of India's four firms are private and locally owned; the fourth is a state government firm. Canada's Inco has a controlling interest in New Caledonia's new chromite mining firm, Societe de la Tiebaghi.

In the past 20 years, there have been shifts in the relative output among chromite producer countries, as shown in table 5-7. Overall, the group of 12 major producers has steadily increased its share of the world market. By 1980 it was providing 98 percent of the world's total production of chromite, up from 90 percent in 1960. During this period, two new producers (Finland and Madagascar) appeared; they now hold 5 percent of the world market. While Albania, Brazil, South Africa, and the Soviet Union have increased their production shares, the shares of the Philippines, Turkey, and Zimbabwe have decreased. The shift from Turkey and Zimbabwe to South Africa is due to the advent of the AOD process and to the accompanying development and aggressive sales by South African firms of "charge chrome," a form of high-carbon ferrochromium particularly suited to South African ores.[17]

The major producer and exporting countries are likely to maintain their current positions in world production for the near future and can be expected to continue reducing the export of ores in favor of ferroalloys. The integration of ore mining with ferroalloy production and the accompanying decline of independent ferroalloy producers may force the remaining nonintegrated ore producers, witnessing shrink-

Table 5-7.—Historical Production—Chromite, 1960-80, by Country
(thousand short tons, gross weight, percent of world total)

	1960		1965		1970		1975		1980	
Producer country	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
Albania	319	7	342	6	516	8	859	9	1,190	10
Brazil	6	<1	19	<1	30	<1	191	2	919	7
Finland	0	0	0	0	133	2	365	4	376	3
Greece	38	1	56	1	29	<1	39	<1	47	<1
India	110	2	66	1	299	4	551	6	354	3
Madagascar	0	0	3	<1	144	2	214	2	198	2
New Caledonia	43	1	0	0	0	0	2	<1	2	<1
Philippines	810	17	611	12	624	9	573	6	547	4
South Africa	851	17	1,038	20	1,573	24	2,288	25	3,763	30
Turkey	531	11	625	12	572	9	790	9	431	3
Soviet Union	1,010	21	1,565	30	1,930	29	2,290	25	3,748	30
Zimbabwe	668	14	646	12	400	6	650	7	608	5
Subtotal	4,386	90	4,971	94	6,250	93	8,812	96	12,183	98
Other	499	10	330	6	422	6	3,324	4	203	2
Total	4,885	100	5,301	100	6,672	100	9,136	100	12,386	100

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbooks* 1964, 1968, 1972, 1977, and 1982.

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[17] See table 5-13 for a comparison of various ferrochromium products.

ing markets, to integrate. Turkey, India, Greece, Albania, and Madagascar, among other countries, are currently expanding or planning to expand or introduce ferrochromium capacity. While some construction has been held up by weak worldwide demand for ferroalloys, expansion will probably resume as the steel industry recovers from the early 1980s recession period. Given chromium's primary use in steelmaking, certain producer countries with growing domestic and export-oriented steel industries—e.g., India and Brazil—may reduce their participation in both ore and ferroalloy export markets.

The 1981-82 worldwide recession caused low-capacity usage in chromite mines (see table 5-8) and ferroalloy plants, and low world prices. These market conditions and the competitive strength of the South African producers inhibit the pursuit and development of new sources of chromite ore. In addition, the only known, nonproducing deposits of chromite are considered marginally economic even under more favorable market conditions due to low grades and/or smallness of overall deposit.

In 1982 one new chromite source entered the world market when a firm resumed production at a previously abandoned area in New Caledonia. A project in Papua New Guinea has been fully explored and evaluated by an international mining firm but is not considered economically viable and will not be developed in the near future. Together, these new producers, while diversifying the world's sources of chromium, will add only about 5 percent, at maximum output, to the world's total production. More important, perhaps, is that new sources of chromite will be unconventional unless new stratiform or podiform deposits are discovered. The Papua New Guinea project, for instance, may undertake mining from a sand and laterite deposit.

In the long term, two developments could alter the current pattern of chromite production. Almost 90 percent of the world's known reserves of chromium are contained in stratiform, as opposed to podiform, deposits. This is explained in part by the fact that stratiform chromite deposits are continuous over large areas, making estimation of reserves relatively easy and the exploration costs to prove large tonnages of reserves small compared to those for podiform deposits. Scattered, discontinuous podiform deposits, on the other hand, are difficult and therefore expensive to locate, even using the most sophisticated geophysical exploration techniques.[18] This implies that areas

Table 5-8.—Chromite Mine Capacity and Usage in 1981 by Country
(thousand short tons, contained chromium)

Producer country	Estimated annual capacity	Percent in use	Estimated unused capacity
Albania	300	50%	150
Brazil	130	83	22
Finland	130	82	23
Greece	15	73	4
India	170	47	90
Madagascar	50	48	26
New Caledonia	5	20	4
Philippines	150	85	23
South Africa	1,500	63	555
Turkey	170	97	5
Soviet Union	1,000	93	70
Zimbabwe	325	43	185
Other	55		
Total	4,000	70	1,160

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Commodity Profile 1983: Chromium.*

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[18] U.S. International Development Cooperation Agency, Trade and Development Program, *The Chromite Project Definition Mission of the Philippines,* February 1983; Charles J. Johnson and Jean A. Brady, *Chromite Potential of the Southwest Pacific,* a summary of research in progress at the Resource Systems Institute of the East-West Center, Honolulu, Hawaii. August 1982, p. 13.

of podiform deposit concentration—e.g., in Turkey, Albania, and the Philippines—that have not been systematically surveyed are potential locations for increased reserves. Location of these podiform deposits could benefit from developments in the use of geochemistry as a prospecting tool and an infusion of funding to finance exploration efforts.

The other possible development is exploitation of two deposit types found in the southwest Pacific Basin area—the Philippines, Indonesia, New Caledonia, New Guinea; that is, nickel laterite deposits overlain by low-grade chromite, and alluvial deposits of chromite sands in shallow offshore areas. No laterites have yet been exploited for chromite, and only one beach sand operation has been opened (in the Philippines). The mining and extraction of chromium from either type of deposit is prevented not by a lack of technology, but by economics. An American mining company studied the possibility of joining in the Philippine beach sand operation and decided that the economics, based on South African competition, did not warrant the investment. The U.S. Bureau of Mines has conducted successful research up to the pilot plant stage on processing laterites ores (from U.S. sources) and concluded that existing technologies, with adjustments for the different minerals encountered in foreign ores, could be applied. Analyses at the East-West Center concluded[19] that economic mining of some known laterite resources would require a chromite concentrate price of $100 to $150 per tonne, f.o.b.[20] (The 1984 price for South African 44 percent chromic oxide chromite ore was $40 to $55 per ton, f.o.b., or $44 to $60 per tonne.)[21] Ongoing work by the U.S. Geological Survey on PGMs contained in laterites (see the PGM section) offer a possibility of changing the economics of laterite deposits if PGMs could be mined as a primary or coproduct.

While expansion of chromite production awaits increased steel industry production, many ore producers have announced plans to add ferrochromium capacity. In some countries, such as Zimbabwe, this would require additional ore production, but in many it could simply mean a greater diversion of ore production from exports into ferroalloy production. Some of the constraints to increased production, such as lack of energy sources and transportation facilities, are given below in brief country-by-country reviews.

Albania

Chromite is one of Albania's chief export commodities and most important sources of foreign exchange.[22] Since 1976, Albania's production has been steadily increasing. The nation now ranks as the world's third largest producer. The last completed 5-year plan period (1976-80) called for an output of 1.25 million tonnes (1.14 tons) by 1980, a goal that was not quite met. The 1981-85 plan calls for a 9.7-percent annual increase in chromite output. Albania has one ferrochromium plant in operation, with total estimated capacity of 30,000 tons per year.

Albania's chromite trade patterns have shifted over the past 30 years. Its production once served as a supplemental source for Eastern European nations that relied primarily on exports from the Soviet Union. China bought half of Albania's output from the mid-1950s to 1978, when relations were broken due to ideological conflicts. Since then, an increasingly large portion of Albania's exports have gone to Western countries. Recently, relations with China have improved, and renewed ties could bring resumed chromite trade. Yugoslavia has been an important buyer of Albanian ores for conversion into ferroalloys for the world market.

While Albanian ore reserves and resources are not known with great certainty, current estimates are considered too low to support current and planned production levels. The possibility of finding new deposits is likely because large areas have yet to be explored for the discontinuous, podiform deposits common to Albania.

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[19] Charles J. Johnson, personal communication, August 1983.

[20] Free on board, means price at embarkation—i.e., without transportation charges.

[21] "AMM Closing Prices," *American Metal Market*, June 21, 1984.

[22] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook*, 1981, vol. III, p. 42.

Brazil

Due to the volume of unexplored area in Brazil, the potential exists for improved chromite reserves but the uncertainty factor is high. Ferbasa is Brazil's major producer of ore and its sole producer of ferrochromium. Brazil exports more of its chromium as ferrochromium than as ore. Most has been destined for Japan, which assisted Ferbasa in the development of its ferrochromium facilities. In 1972 a Japanese consortium formed a joint venture (Mineracao Serra de Jacabina S.A.) with Ferbasa to mine another deposit, in the state of Bahia. The mine was opened in 1976 and was Japan's first captive overseas chromite mine. Heavy losses forced the Japanese to sell their 48-percent interest to Ferbasa in 1980.

Finland

Finland's sole producer of chromite, Outokumpu Oy, is a highly integrated firm that mines, explores, trades, smelts, and refines a variety of minerals and produces both ferrochromium and stainless steel. In addition, it is involved worldwide in the development and sale of mineral industry technology. Currently, all of Outokumpu's chromite production comes from its Kemi deposit, located in northwestern Finland near the Gulf of Bothnia. Another deposit is being developed for future production and would allow, under the proper economic conditions, a 25-percent increase in Finland's output. A constraint on expansion is the need to import energy resources—mainly petroleum. Shipping during the winter months is often hampered by frost and ice conditions.

Greece

An expansion in chromite mining and in development of a ferrochromium industry has been underway in Greece since 1976, when government geologic research verified that chromite resources were adequate for ferrochromium production. Hellenic Ferroalloys S.A. has expanded an underground mine at the Skoumtsa deposit in the Mt. Vourinos region (northern Greece, near the Albanian border) to serve as feed for a new ferrochromium plant at Tsigeli. This plant, which began operation in February 1983, was constructed by Outokumpu Oy. Until Hellenic Industrial Mining & Investment Co. (parent firm of Hellenic Ferroalloys) follows through with plans for a steel plant at Tsigeli, the ferrochromium output (potential total capacity of about 90,000 tons per year) is destined for the export market, primarily other European Economic Community (EEC)[23] countries.

India

The principal ore-producing area in India is in the state of Orissa. In recent years, the Indian government has actively encouraged the development of the ferrochromium industry to increase the value of its exports and to reduce its dependence on imported ferroalloys for growing domestic steel needs. Four new plants were under construction in 1982 for two private firms and one public firm. Ongoing mining industry upgrading and geological survey work to improve the ore reserve base is intended to support the ferroalloy industry rather than increase ore exports. Production has been hindered at times in recent years because of power shortages caused by droughts. Indian power needs are heavily dependent on the monsoon rains to provide necessary energy. Transportation bottlenecks and production inefficiencies are traditional constraints to India's assuming a greater role in providing world needs.

Madagascar

Chromite is this country's most important mineral commodity, and all production is for export. Although feasibility studies have been conducted, no ferrochromium plant has yet been built, owing to unresolved financial and technical problems. The necessary power source, a hydroelectric dam, was completed in 1983. Two open pit mines, each with a capacity of 300,000 tons of chromite ore per year, are operated. The Adriamena mine was developed by the French firm Comina before it was nationalized in 1976. Its ores must be processed to reduce an unacceptably high phosphorus level. The newer mine, Befandriana, is a primitive setup consisting of several small open pits and no concentrator. Ores from this mine do not have a high phosphorus level and are simply screened to produce two separate grades. During monsoon season, December to April, the Befandriana pits cannot be operated. Transportation from Adriamena is by truck and railroad to the port of Toamasina (Tamatave). From Befandriana, ores are trucked about 100 miles to Narinda Bay for shipment. Due to the shallowness of the bay, ores must be transferred by small vessels to ocean freighters; loading of one shipment can take 3 weeks.

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[23] Common Market.

The area has the potential to expand production easily by 50 percent due to the extent of the reserves. Transportation is the weakest link; lack of sufficient railroad cars, poor roads, and the undeveloped port at Narinda Bay impede expansion. While France is Madagascar's major customer for chromite, one U.S. ferroalloy firm, Interlake, had a 2-year contract, ending in 1982, to take all of the annual output of the Befandriana mine. The contract has not been renewed due to the weak market for ferroalloys.

New Caledonia

All of New Caledonia's lateritic nickel deposits contain chromite. Much of the chromite, however, occurs in low grades and is currently considered uneconomical. Two firms operate mines from podiform deposits in New Caledonia. Societé de la Tiebaghi started full-scale production in 1982, with an output of 50,000 tons of chromite concentrates (containing 51 percent chromic oxide), eclipsing Calmine's 2,000 tons-per-year operation. Capacity of the Tiebaghi mining operation is 85,000 tons per year of concentrates. The new mine, for which development work began in 1976, underlies a Union Carbide operation that closed in 1962. The island has no domestic energy source, creating a potential barrier for any expansion. Societe le Nickel (SLN), the large nickel producer on the island, already consumes 85 percent of the country's industrial elecricity in its mining and smelting operations. A hydroelectric powerplant has been considered but is not yet planned.

Philippines

The Philippines is the principal source of refractory grade chromite for the Western world. The Coto deposits in the Zambales district on the main island of Luzon are the largest such group in the world. Reports on the Philippines continually predict reserve depletion, but further exploration has always extended mine life by another 10 years. Two major firms conduct operations at Zambales. Consolidated's Masinloc mines are operated by the Benquet Corp. and contribute 95 percent of the country's refractory ores; Acoje Mining is the country's major metallurgical ore producer. A third firm, Trident Mining & Industrial Corp., has produced metallurgical ores from mines on the southern Palawan Island. Its operations have been shut down since 1981 due to financial problems. Representatives from Trident were in the United States in 1983 seeking new capital to resume production and reportedly secured it. In late 1983, Acoje was seeking debt relief from the Philippine government and the private sector in order to maintain operations. These financial difficulties will delay plans for exploration and new mine development.

Two ferrochromium plants in the Philippines produce primarily for the Japanese market. The newest plant began operating in 1983, and some startup problems caused by erratic power supplies and ore quality were reported.

Theoretically, the extensive ultramafic formations of the Philippines could hold up to 105 million tons of 32-percent chromic oxide in laterite formations.[24] Extensive, systematic geological field and exploration work, however, must be completed in order to prove the theory.

South Africa

The Bushveld Complex in the Transvaal Province is the largest known chromite deposit in the world. Most of the chromite is produced in two districts within the complex: the Eastern Belt (Lydenburg district, five mines) and Western Belt (Rustenburg district, eight mines). Competition among the many firms and mines for increased market shares is strong. The slackness in world chromite markets, rising costs, and stable prices in recent years have caused some of the least efficient mines to be placed on "care and maintenance" status.

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[24] *The Chromite Project Definition Mission of the Philippines*, op. cit.

The UG2 (upper group seam of the Bushveld) chromium-platinum reef in Rustenburg is currently mined for PGMs by Western Platinum and has chromite resources estimated by South Africa to total 650 million tonnes. Tapping certain sections of this reef for chromium requires new metallurgical and smelting techniques in order to separate and recover the individual minerals. The South African government's Mintek (Council for Mineral Technology, a research arm of the Ministry of Mines and Energy) has conducted research and development and plasma technologies, which provide high-temperature processing, have been tested. Western Platinum has reportedly opened a smelter in 1984 capable of processing these complex ores and is considering the addition of a ferrochromium plant.

As in many areas, transportation bottlenecks could limit any effort to rapidly increase output from the Bushveld. Ores from the mines are currently trucked 5 to 10 miles to a railhead. Once there, the ores are moved to the heavily used port of Maputo in Mozambique (480 miles from the Western Belt and 350 miles from the Eastern Belt). Perennial congestion at the port has been relieved by recently installed mechanized facilities. The port can now handle 2,500 tonnes of chromite per hour and store up to 1.1 million tonnes. Alternate ports in South Africa, at Durban and Richards Bay, could be used if Maputo was not available (for instance, due to transborder conflicts) although significant lead-time would be required to accommodate chromite at these ports. It has been estimated that for a typical underground South African mine, 50-percent expansion would require little more than 1 year; however, port expansions to handle such increased output could take 4 years.[25]

Soviet Union

The Soviet Union is still the world's second largest chromite producer, although its ore exports have declined during the past decade. Most of its deposits are podiform and located in the Ural Mountains. Virtually all its metallurgical-grade ores originate in the Western Kazakhstan (southern Ural region). Ninety percent of production comes from the Donskoye mining and concentration complex in Khrom-Tau. A new underground mine there started producing in 1982 with an expected ore capacity of 2 million tons per year by 1985.

Turkey

Exports of ore from Turkey have declined in recent years as a result of increasing internal consumption, world market oversupply, and an inability to meet price competition. Turkish podiform deposits are widely scattered (occurring in 40 of the country's 67 provinces), limiting the output and mechanization potential of many mines. The presence of podiform rather than stratiform deposits, however, makes the total resource picture uncertain because such pockets are difficult to locate. With economic incentives, a 50-percent increase in production (a return to the 1975 production level) could take place in 3 to 12 months. Any further increase would be limited by available and willing investment and would require an increase in reserves. Constraints would include lack of mining equipment and transportation bottlenecks. The main ports (Mersin and Iskenderun, on the Mediterranean Sea) are 400 miles from the mineheads and have maximum loading capacities of 3,000 tonnes per day, each.

Several ferrochromium plants are now online in Turkey, and additional capacity (to a total 150,000 tons per year) is expected by 1986. Etibank, the state-owned mining company that supplies half of Turkey's chromite output and all of its ferrochromium, has a reputation for making policy decisions removed from political influence. Under the most recent government it has become very active in seeking investment partners from the private sector. Owing to market conditions, most of Turkey's existing private producer mines, which mainly contribute ores for export, were closed during 1982. Overall, Turkey's chromite industry could improve its position in the world market with an infusion of capital and substantial technology transfer to upgrade its mining and processing procedures.

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[25] Charles River Associates, *Processing Capacity for Critical Materials*, contractor report prepared for the Office of Technology Assessment, January 1984.

Zimbabwe

Most of the chromium reserves in Zimbabwe lie in the Great Dyke, an elongated, elevated geological structure that runs 300 miles or more in a northeast-southwest direction across the country. However, about 80 percent of current output comes from the Selukwe mines in related lode deposits along the Great Dyke's southern section. The Dyke's thin seams require labor-intensive mining methods and are underdeveloped due to high costs. The Selukwe mines are operated by Union Carbide's Zimbabwe Mining & Smelting Co. Since Western trade sanctions against the importation of Rhodesian (now Zimbabwean) chromium were lifted in 1979, the emphasis has been on exporting ferrochromium rather than ores. Union Carbide and Anglo American (of South Africa) own the two ferroalloy plants in Zimbabwe. Their combined ferrochromium capacity in 1980 was 240,000 tons per year, and expansion plans have been announced. As with most chromite mining areas, transportation is a major physical barrier to increased production. Zimbabwe would prefer to use direct rail routes through black Mozambique, but while the border was closed between 1975 and 1980, the rail link deteriorated, forcing reliance on routes through the ports in South Africa.

Potential Producers

PAPUA NEW GUINEA—RAMU RIVER

A nickel laterite deposit containing chromite and cobalt has been under development at Ramu River. The mineral deposit is in three layers, with chromite in the top two layers. Estimates give a reserve of 80 million to 100 million tons of ore with about 9 percent metallurgical grade chromite in the first, sandy clay layer, and about 81.5 million tons at 6 percent in the second. These 14 million tons of chromite would place Papua-New Guinea alongside most of the major ore-producing countries, if classified as a reserve and assuming a chromic oxide content of 46 percent. Nickel (1.14 percent) and cobalt (0.16 percent) are concentrated in the third layer of the deposit. In 1983 Nord Resources Corp. (U.S.) held a 69.5-percent share of the mining concession and Mount Isa Mines Ltd. (Australia), the balance. (Mount Isa Mines is owned by the Australian corporation M.I.M. Holdings, in which Asarco Inc. holds a 49-percent interest.) Technical viability of the project has been confirmed, and economic studies were conducted in 1982. An executive of Nord Resources stated in early 1984 that the earliest possible date to start the development phase of the project was 2 years away due to the depressed markets for both chromite and cobalt, and that once a decision to go ahead was made—if ever—it would take 5 years to reach the production phase.[26]

The first phase of production will be to mine the chromite, which can be recovered from the ore by gravity concentration methods. Nickel and cobalt, which will require a hydrometallurgical acid leaching process for recovery, will be mined in the second stage of the project. Annual production of chromite concentrates has been estimated at 500,000 tons. Japan, Australia, and the United States are considered the most probable markets. The U.S. Bureau of Mines tested the chromite concentrate product and, using conventional technology, produced high- and low-carbon ferrochromium.[27]

CANADA—BIRD RIVER

Of hundreds of documented chromite occurrences in Canada, few contain measured resources. One deposit, considered the most likely candidate if development plans arise, is Bird River in Manitoba. Resources for the four Bird River properties total 4 million tons at 18 to 25 percent chromic oxide and 15 million tons at 5 to 7 percent chromic oxide.

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[26] Richard Steinberger, Executive Vice-President, Nord Resources, Dayton, OH, personal communication, February 1984.

[27] "More on Ramu River," *Mining Journal*, Mar. 19, 1982, p. 211 and U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982*, vol. III, p. 1237.

The low grade and chromium-to-iron ratio of these deposits have mitigated against their development in the past. Research into technologies to process the ores has determined that only with high-cost chemical treatment can a sufficiently high-grade product be attained to meet conventional specifications. Recent research by the Ontario Research Foundation has produced a chromium carbide that could be used to produce chromium metal or be used as an alloying agent.

Domestic Production of Chromium

Known resources of domestic chromite are the stratiform deposits in the Stillwater Complex of Montana and the small podiform bodies in northern California, Oregon, and Alaska. Chromite is also associated with nickel-cobalt laterite ores of northern California and southern Oregon and found in placer beach and stream sands located in Oregon, Maryland, and Pennsylvania.

As tables 5-9 and 5-10 show, the United States has an estimated 337 million tonnes (371 million tons) of identified resources[28] of chromite with chromic oxide grades ranging from 1 to 25 percent (or, 13.8 million tons of contained chromium). Of these identified resources, 80.4 million tonnes (88.6 million tons) of chromite are considered to be demonstrated resources (a subdivision of identified resources with the highest degree of geologic certainty) containing 3.9 million tons of chromium. As a comparison, South Africa is credited with a "reserve base" (total demonstrated resources but excluding the subeconomic tonnages) of 910 million tons of shipping grade chromite ores normalized to 45 percent chromic oxide, or 279 million tons of chromium.

In a Minerals Availability Appraisal[29] published in 1982, the U.S. Bureau of Mines concluded that none of the U.S. identified resources of chromite in stratiform or podiform deposits were economically recoverable at January 1981 market prices ($128 to $144 per tonne for a metallurgical grade product, CIF[30] in the Eastern United States). Instead, production at that time would have required a minimum price of $237 per tonne, almost double the prevailing market price.

Laterite deposits were not analyzed in the Bureau of Mines' study in terms of potential production because of "technological and cost uncertainties."[31] Unlike laterite deposits, the other deposit types have previous production history in the United States.

The mining and beneficiation methods upon which the study was based were those methods used in past domestic production of chromite ores; no new technologies were considered. For each deposit included in the appraisal (table 5-11), the engineering and cost (capital and operating) analyses were followed by an economic evaluation using a 15 percent rate of return on the capital investment. Some costs were not considered—e.g., the time lags involved in filing environmental impact statements, receiving necessary permits, financing, etc., as it was felt that such delays "would be minimized in consideration of strategic availability."[32]

Up to 235,000 tons per year (table 5-12) of contained chromium could theoretically be produced from the most probable U.S. sources. This assumes simultaneous production and would most likely require government incentives. Mine lifetimes range from 3 to 46 years.

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[28] "Identified" resources are those for which location, grade, quality, and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic, and subeconomic components. To reflect varying degrees of geologic certainty, identified resources are divided into "demonstrated" (both measured and indicated) and "inferred" resources.

[29] Jim Lemons, Jr., et al., U. S. Department of the Interior, Bureau of Mines, *Chromium Availability—Domestic: A Minerals Availability System Appraisal*, Information Circular No. 8895, 1982, p. 1.

[30] Cost, insurance, and freight paid by the shipper.

[31] Ibid., p. 1.

[32] Ibid., p. 7.

Table 5-9.—U.S. Chromite Deposit Resources

			Demonstrated[a] (thousand tonnes)		Identified (thousand tonnes)	
State	Property	Grade (percent Cr_2O_3)	Mineralized material	Contained Cr_2O_3	Mineralized material	Contained Cr_2O_3
Alaska	Claim Point	17.6	267	47.6	267	47.6
	Red Bluff Bay	12.0	30	3.6	30	3.6
	Red Mountain	25.8	0	0.0	183	47.2
California	Bar Rick Mine	7.6	5,065	384.9	44,512	3,382.9
	McGuffy Creek	W	W	W	W	W
	North Elder Creek[b]	11.9	0	0.0	104	12.4
	Pilliken Mine	5.0	0	0.0	30,975	1,548.8
	Seiad Creek/Emma Ball	5.0	4,546	227.3	10,826	541.3
Georgia	Louise Chromite	.4	131	.6	131	.6
Maryland-Pennsylvania	West Placer Area[c]	1.4	729	10.1	729	10.1
Montana	Stillwater Complex:					
	Mouat/Benbow	W	W	W	W	W
	Gish Mine	15.0	500	75.0	854	128.1
North Carolina	North Carolina Area[b]	1.9	108	2.1	178	3.5
Oregon	Southwest Oregon Beach Sands	5.6	10,827	604.1	45,772	2,554.1
Pennsylvania	Renshaw Placer	1.7	209	3.5	209	3.5
Wyoming	Casper Mountain	2.5	3,774	92.5	3,774	92.5
Total[d]		NA	46,604	5,620.6	194,019	19,333.2

W—Withheld to avoid disclosing individual company proprietary data; included in total.
NA—Not applicable.
[a] Domestic chromite reserve base.
[b] Includes 3 deposits that have been combined for analysis.
[c] Includes 13 deposits that have been combined for analysis.
[d] Includes resources withheld to avoid disclosing individual company proprietary data.

SOURCE: U.S. Department of the Interior, Bureau of Mines Information Circular No. 8895, 1982, *Chromium Availability—Domestic: A Minerals System Appraisal*, tables 1 and 2, pp. 4 and 5.

Table 5-10.—U.S. Chromite Laterite Deposit Resources

			Demonstrated (thousand tonnes)		Identified (thousand tonnes)	
State	Property	Grade (percent Cr_2O_3)	Mineralized material	Contained Cr_2O_3	Mineralized material	Contained Cr_2O_3
California	Gasquet Laterite	W	W	W	W	W
	Little Rattlesnake	W	W	W	W	W
	Lower Elk Camp	W	W	W	W	W
	Pine Flat Mountain	2.8	6,382	178.7	15,052	421.5
	Red Mountain	W	W	W	W	W
Oregon	Eight Dollar Mountain	1.1	0	0	13,023	145.9
	Red Flat	W	W	W	W	W
	Rough and Ready	1.5	0	0	5,931	90.7
	Woodcock	1.3	0	0	8,587	112.5
Total		NA	33,813	640.0	143,126	2,995.4

W—Withheld to avoid disclosing individual company proprietary data; included in total.
NA—Not applicable.

SOURCE: U.S. Department of the Interior, Bureau of Mines Information Circular No. 8895, 1982, *Chromium Availability—Domestic: A Minerals System Appraisal*, tables 1 and 2, pp. 4 and 5.

Table 5-11.—Proposed Mining and Processing Methods U.S. Chromite Deposits

Property	State	Type of deposit	Minimum lead time years	Annual capacity tonnes of ore	Mining method	Beneficiation method
Claim Point	Alaska	Podiform	4	18,000	Open pit	Gravity
Red Bluff Bay	Alaska	Podiform	2	9,000	Open pit	Gravity
Red Mountain	Alaska	Podiform	2	18,000	Overhand shrinkage	Gravity
Bar Rick Mine	California	Podiform	2	350,000	Sublevel slope	Gravity
McGuffy Creek	California	Podiform	2	787,000	Open pit	Gravity
North Elder Creek[a]	California	Podiform	1	25,000	Open pit	Gravity
Pilliken Mine	California	Podiform	2	2,100,000	Open pit	Gravity-magnetic
Seiad Creek/Emma Bell	California	Podiform	3	562,500	Open pit	Gravity
Louise Chromite	Georgia	Placer	1	25,000	Open pit	Gravity-electrostatic
West Placer Area[b]	Maryland-Pennsylvania	Placer	1	50,000	Placer mining	Gravity-electrostatic
Stillwater Complex:						
Mouat/Benbow	Montana	Stratiform	3	525,000	Shrink slope	Gravity
Gish Mine	Montana	Stratiform	2	175,000	Shrink slope	Gravity
North Carolina Area[a]	North Carolina	Placer	1	25,000	Open pit	Gravity-electrostatic
Southwest Oregon Beach Sands	Oregon	Placer	2	1,000,000	Strip	Gravity-magnetic-electrostatic
Renshaw Placer	Pennsylvania	Placer	1	50,000	Open pit	Gravity-electrostatic
Casper Mountain	Wyoming	Stratiform	3	377,260	Open pit	Gravity

[a] Includes 3 deposits combined in the analysis

[b] Includes 13 deposits combined in the analysis.

SOURCE: U.S. Department of the Interior, Bureau of Mines Information Circular No. 8895, 1982, *Chromium Availability—Domestic: A Minerals Availability System Appraisal,* tables 1 and 2, pp. 4 and 5.

All of these areas, with the exception of Gasquet Mountain in California, have been mined previously, providing a backlog of information and infrastructure upon which to base operating decisions. Gasquet Mountain has benefited from considerable recent commercial evaluation.

The most recent U.S. production of chromite was from the Gish and Mouat/Benbow Mines at Stillwater from 1953 until 1961, subsidized by the Federal Government under the Defense Production Act. The contract with the American Chrome Co. called for 900,000 tons of chromite ore (36 to 38 percent chromic oxide) over an 8-year period (an average annual rate of 113,000 tons), during which the government advanced $1.8 million for machinery and equipment and guaranteed the company a price of $34.98 per ton of ore (about $140 per ton of chromium). (During the period 1954-61, the weighted average yearly price ranged from $124 to $147 per ton.)[33] Approximately 400,000 tons of the ore produced—half of the contract—remained unused and was sold by the government to Metallurg, Inc., in 1974 for $7.64 per ton. In 1984, this "stockpile" sat in the town of Columbus, nearby the Stillwater mine site.

Chromite was also mined from Stillwater and from podiform deposits in Alaska under World War II production subsidies. At Stillwater, development efforts began in 1941 under the Reconstruction Finance Corp.'s Metals Reserve Co. After spending $15 million on the development of two mines (only one of which actually started producing), all operations were closed down in 1943 when foreign trade routes became more secure. Domestic chromite production reached a historic peak of about 140,000 tons in 1943, and consumption that year was

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[33] U.S. Department of the Interior, Bureau of Mines, *Mineral Facts and Problems,* 1975 edition, p. 248.

Table 5-12.—Potential U.S. Chromite Production

	Demonstrated resources			Estimated annual production		
Known resources by deposit type	Grade (percent Cr_2O_3)	Ore (thousand tonnes)	Chromium content (thousand tonnes)	Ore (thousand tonnes)	Chromium content (thousand tonnes)	Estimated minelife (years)
Stratiform:						
Stillwater Complex:						
Mouat/Benboe	W	W	W	525	72[a]	46
Gish	15.0	500	51	175	16	3
Podiform:						
California:						
Bar Rick Mine	7.6	5,065	262	350	16	13
McGuffy Creek	W	W	W	788	NA	4
Pilliken Mine[b]	5.0	30,975	1,053	2,100	65	4
Seiad Creek/Emma Bell	5.0	4,546	155	563	17	9
Beach Sands:						
Southwest Oregon	5.6	10,827	412	1,000	35	11
Laterite	Grade (percent chromium)	Proven reserves (thousand tonnes)		Chromite concentrates (thousand tonnes)		
Gasquet Mountain	2.0	16,000	320	50	14	18

[a] Estimated assuming 15 percent grade.
[b] Inferred resources only.
W—Information withheld for proprietary reasons.
NA—Date not available.

SOURCES: Resources, ore grades, proposed mining rate, minelifes from U.S. Department of the Interior, Bureau of Mines, *Chromium Availability—Domestic*, IC8895/1982. Gasquet Mountain data provided by California Nickel Corp; balance calculated by OTA.

Chromium data	1979	1982
Reported chromite consumption (tons) (22 to 38 percent chromium)	1,209,000	545,000
Apparent chromium consumption (tons)	610,000	319,000

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries*, 1984.

965,000 tons. More than 200,000 tons has been reported as domestic "shipments" for 1956, but some 45,000 tons of this amount came from government stockpiles.

Before 1958, scattered small chromite deposits were mined in California, Oregon, and Washington. The Pilliken Mine near Sacramento, CA, for instance, was operated intermittently from 1950 to 1957. Total production from these mines was, however, never more than 45 percent of the Stillwater Complex production in the same years.[34]

Stillwater Complex

The chromite deposits at the Stillwater Complex in Montana are the largest known, single potential U.S. source of chromium. Although there are no current plans to resume commercial production of chromite at Stillwater, these deposits would most likely be the first to be considered for production during any emergency situation. Several companies, including Anaconda Minerals Co., which has patented mineral holdings on the Mouat/Benbow Mine, have been involved in the area since the late 1960s in investigating various Stillwater properties for their potential mineral values. (See the domestic PGM section, p. 196 for details.)

Available resource data for the two chromite deposits, the Gish and Mouat/Benbow mines, are not complete since for proprietary reasons only the numbers for the Gish mine have been published (see table 5-9). The Mouat/Benbow deposit is reportedly the much larger of the two. This is evident from the fact that the Bureau of Mines projected a mine life for the Mouat/Benbow deposit of 46 years with a production rate of 525,000 tonnes (477,000 tons) of ore per year; whereas, production at the Gish mine was projected at a third of that rate for only 3 years.

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[34] For more information about past domestic production see, Silverman, et al., op. cit., and *The Stillwater Citizen-Sun*, Apr. 26, 1974, sec. 2, p. 8.

Combined potential output of 65,000 tons of contained chromium (table 5-12) from these Stillwater mines amounts to about 11 percent of U.S. needs when compared with a peak consumption year such as 1979 or 20 percent when compared with 1982.

Gasquet Mountain Prcject

California Nickel Corp. has proposed to produce nickel, cobalt, and chromium from a lateritic deposit at Gasquet Mountain in northern California. The project's economic viability is dependent on the market prices of all three metals, and in 1982 the firm was using a chromite price of $40 per ton in its economic evaluations. The estimated output (50,000 tons per year of chromite concentrates with 14,000 tons of contained chromium) would be small relative to the other metals involved in the project and in relationship to Stillwater as analyzed by the Bureau of Mines. However, this is the only domestic mining project which includes chromium that has been under recent scrutiny by a mining firm. Perhaps of greater importance is the processing technology that this firm is developing for recovery of metals from laterite ores. Such ores have the possibility of being a future worldwide source of metals such as chromium, nickel, cobalt, PGMs, etc. (The Gasquet Mountain Project is discussed in more detail in the cobalt section on p. 170. See also the following chromium mining and processing technologies section on p. 153.)

Lateritic deposits generally offer one of the lowest metal grades, and chromite at Gasquet is thought to be extremely erratic. Exploitation thus requires considerable movement of ore in order to reclaim any substantial tonnages of the desired metal.

Other Potential U.S. Sources

Other chromite deposit types in the United States are the podiform bodies in northern California, southern Oregon and Alaska and beach sands in Oregon, Maryland, and Pennsylvania. Table 5-12, using the Bureau of Mines' analysis, shows the estimated production from the most likely candidate areas, California's podiforms and Oregon's beach sands.

Although the chromium content of the possible output of the Pilliken Mine was calculated as the largest, the information base is the weakest since all resources fall into the "inferred" category. Except for the Bar Rick Mine, these podiform properties have short mine lifes which reduces their economic viability.

The Oregon beach sands contain a comparatively large amount of identified resources. These resources are dispersed over a large area (some 5,000 acres) which is now either public beaches or land used in Oregon's forestry industry. The low grades present means that a lot of material would need to be displaced in order to acquire the contained chromite, disturbing not only the beaches but an established Oregon economic base.

The Alaskan podiform deposits are considered the most expensive to mine, due to their location, low grades and short mine lifes. One area of podiform deposits, stretching south from Anchorage through the Kenai Peninsula along the Chugach Arch, may contain sufficient chromite for several years supply, but is not of commercial interest due to the high cost of production.[35] Anaconda Minerals explored one such deposit area, Red Mountain near Seldovia, as a possible PGM resource but results have proved disappointing. Conceivably, chromite might be a byproduct of any future PGM production there. Other potential occurrences of chromite in Alaska are at Kanuti River, Red Bluff Bay, Baranof Island, in southeastern

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[35] John Mulligan, Chief, Alaska Field Operations Center, Bureau of Mines, personal communication, July 9, 1984.

Alaska, and the western Brooks Range deposits. Present information on these occurrences is inadequate to suggest any level of expectation.[36] After surface occurrence investigations in the Kanuti River area, the Bureau of Mines recommended in 1983 that subsurface exploration be employed to establish the extent of chromite occurrences.[37]

Domestic Mining and Processing Technology Prospects

Rather straightforward mining and beneficiation technologies are applicable for the exploitation of U.S. chromite deposits, and their composition—while primarily chemical grade —is suitable for a variety of current uses. Future breakthroughs in beneficiation and smelting technologies might lead to the possibility of mining of lower grade ores common to the United States. Plasma arc furnace technology (see the following processing section), for instance, uses finely ground chromite as is found in laterite deposits. Successful application of new methods would not necessarily make U.S. deposits more competitive with other world deposits, unless innovations can be selectively applied to U.S. deposits.

Improved mining technology offers several possible applications for chromite ore mining. In hardrock ore bodies, open pit and underground mining systems would be similar to those used in other ore bodies; the trends toward increased mechanization and to continuous mining systems would apply. The new vertical crater retreat system for underground mining would be especially applicable in narrow and steeply dipping veins and podiform bodies. In shallow lateritic material and beach placer type sands, open pit mining would very likely involve continuous mining by bucket wheel machines or by shovels without the need for drilling and blasting.

Solution mining of chromite is only in the conceptual stage, but could provide an approach to the mining of hardrock chromite with explosive fracturing or to the mining of lateritic deposits that are inaccessible by open pit mining.

The minimum grades required for metallurgical use (at least 46 percent chromic oxide and a chromium-to-iron ratio greater than 2.5:1) have not ordinarily been obtained from the processing of domestic chromite deposits. Low-cost methods of beneficiating domestic deposits to an acceptable concentrate have been studied for a number of years by the Bureau of Mines. The methods have involved combinations of gravity and electrostatic separation plus flotation to obtain a higher chromium content, and leaching to reduce the iron content. The Bureau of Mines has recently introduced a chromite beneficiation program that has provided encouraging results. Research has not yet provided for an economic method of upgrading, however. A direct smelting process for Stillwater Complex ore has been investigated; this would provide a high-iron alloy, but still not comparable in grade and cost with imported ferrochromium.

The Albany Research Laboratory of the Bureau of Mines has been exploring the recovery of chromite from the residue of laterites that have been chemically processed to recover cobalt and nickel. Lateritic ores containing chromium are ordinarily roasted and leached. An experimental plan by the Bureau of Mines for the recovery of chromium from laterite ores, as at Gasquet Mountain, involves roasting and leaching after gravity beneficiation, with final electrowinning for nickel and cobalt and final recovery of chromium from the leach residue. The concentrate produced contains about 35 percent chromic oxide. Future research and experimentation in chromite recovery and chromium extraction will most probably involve such hydrometallurgical processing.

Another Bureau of Mines project is evaluating the low-grade podiform deposits of California. These ores range from 3 to 10 percent chromic oxide and contain tonnages that can potentially be mined by open pit and underground methods. Preliminary results suggest that these podiform ores can be concentrated to a range of 37 to 45 percent chromic oxide; and with improved gravity process techniques, a marketable concentrate might be produced if smelter facilities were located nearby and local steel markets were accessible to the product.

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[36] U.S. Department of the Interior, Bureau of Mines, *Critical and Strategic Minerals in Alaska*, Information Circular No. 8869, 1981.

[37] Jeffrey Y. Foley and Mark M. McDermott, U.S. Department of the Interior, Bureau of Mines, *Podiform Chromite Occurrences in the Caribou Mountain and Lower Kanuti River Areas, Central Alaska*, Information Circular No. 8915, 1983.

Foreign and Domestic Chromium Processing

The major use of chromium is as an alloying agent in chromium and stainless steels and in superalloys. In steels, chromium is consumed primarily in the form of a chromium ferroalloy, principally high-carbon ferrochromium or "charge chrome." In the production of superalloys with little or no iron content, a metallic form of pure chromium is consumed. The various types of chromium ferroalloys and metals and their compositions are shown in table 5-13.

Figure 5-1 provides a simplified flow chart of chromium from ore to industrial use. Ore, as produced from today's mines, contains from 35 to 48 percent chromic oxide. An exception is Finland which has the lowest grade economic deposits at 27 percent Cr_2O_3. Where necessary, mined chromite is concentrated (gravity or magnetic separation is usually employed to increase the chromic oxide or reduce the silicon content), sized, and classified at the mine site. This concentrate, typically 40 to 46 percent chromic oxide (27 to 31 percent contained chromium), is then processed by smelting into ferrochromium products or begins a multistep process for conversion into pure metal.

Table 5-13.—Composition of Chromium Ferroalloys and Metal (weight percent)

Type	Chromium	Carbon	Silicon
Ferrochromium:			
High carbon	52-72	4.0-9.5	3-14
Charge	58-60	6-7	4-5
Low carbon	60-75	.025-.75	1-8
Silicon	34-42	.05-.06	38-45
Metal:			
Aluminothermic			
Vacuum melting grade	99.5	.05	.04
Carbothermic (chrome 98)	≈98.5	NA	NA
Electrolytic	99.1	.02	.01

NA—Not available.

SOURCE: Ferrochromium content, U.S. Department of the Interior, Bureau of Mines, *Minerals Commodity Profile 1983: Chromium*.
Metal content, appropriate manufacturers.

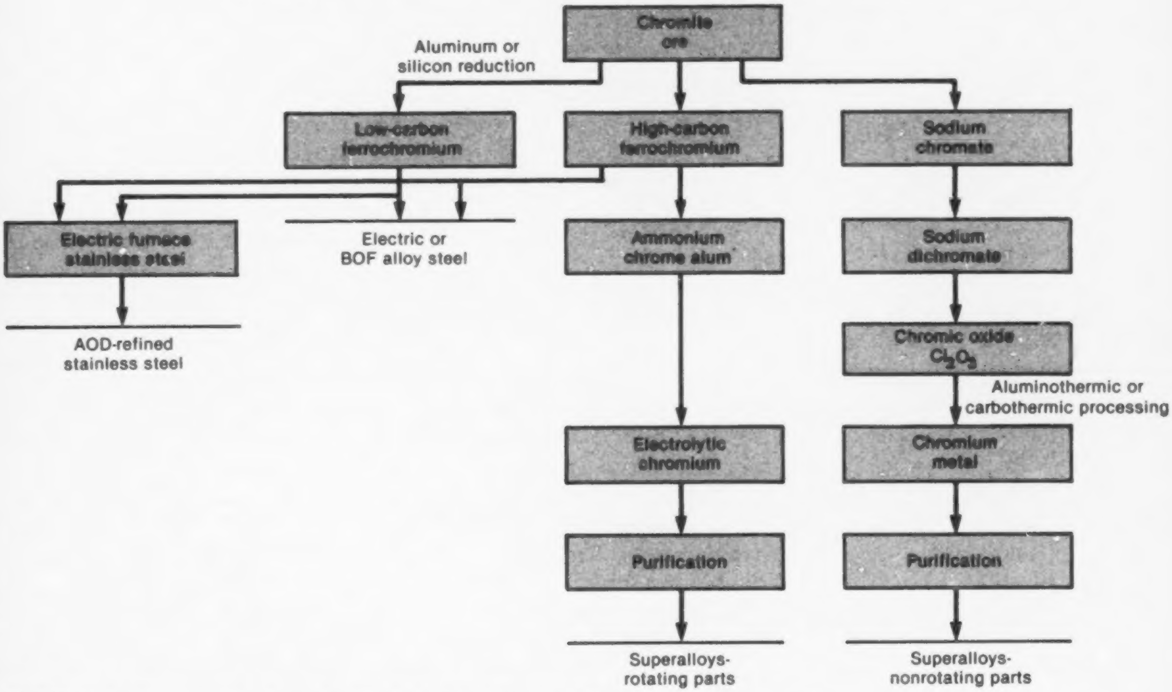
Ferrochromium

High-carbon ferrochromium is usually produced in a submerged arc electric furnace. These furnaces, shown in figure 5-2, use vertical electrodes that are suspended into the charge material (principally chromite and coke, a form of coal). A pass of electric current through the charge provides the heat to sustain a reaction in which the oxygen content of the chromite is removed (by combining with the carbon in the coke) and an iron-chromium alloy is produced.

Low-carbon ferrochromium can be produced from high-carbon ferrochromium or from chromite ores. In the Simplex process, an oxide material is mixed with the ferrochromium and heated in a vacuum furnace, where the carbon and oxide combine and are driven off, reducing the carbon content of the ferrochromium. In another process, silicochromium (a silicon-chromium alloy) is first produced in a submerged arc furnace and then used to reduce the carbon content of ferrochromium in an open arc furnace. (In open arc furnaces the electrodes are not suspended deep within the charge).

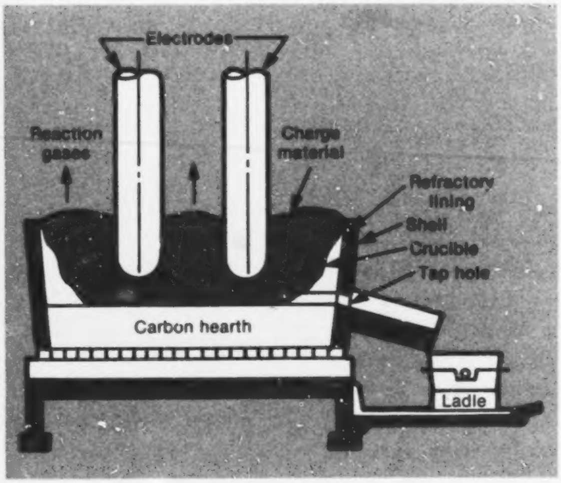
Ferromanganese (see manganese processing section) is produced in electric submerged arc furnaces similar to those used for ferrochromium, and there is a degree of convertibility between chromium and manganese ferroalloy furnaces. The United States has, consequently, some flexibility in production capacity for both ferroalloys. Ferromanganese production requires a wider electrode spacing than that used for ferrochromium, which has a less conductive slag. Other important differences in design parameters of the furnaces include electrode diameter, hearth diameter, crucible depth, and voltage range of the transformer. A ferromanganese electric furnace could technically be used to produce ferrochromium. By techniques such as modifying the composition of the slag to decrease its resistance, the furnace would be operating at less than optimum conditions and would probably not be economic. Modification of these furnaces for alternative uses may be physically and process constrained by the existing pollution abatement equipment.

Figure 5-1.—Simplified Flowchart, Chromium Ore to Industrial Use


Chromite ore
Aluminum or silicon reduction
Low-carbon ferrochromium
High-carbon ferrochromium
Sodium chromate
Electric furnace stainless steel
Electric or BOF alloy steel
Ammonium chrome alum
Sodium dichromate
AOD-refined stainless steel
Chromic oxide Cl_2O_3
Aluminothermic or carbothermic processing
Electrolytic chromium
Chromium metal
Purification
Purification
Superalloys-rotating parts
Superalloys-nonrotating parts

SOURCE: Charles River Associates, *Processing Capacity for Critical Materials*, OTA contract report, January 1984.

Figure 5-2.—Submerged Arc Furnace


Electrodes
Reaction gases
Charge material
Refractory lining
Shell
Crucible
Tap hole
Carbon hearth
Ladle

SOURCE: Charles River Associates, *Processing Capacity for Critical Materials*, OTA contract report, January 1984.

ADVANCED TECHNOLOGY

While the submerged-arc electric furnace process predominates in the production of ferroalloys, other methods are being explored. Most attention is directed at the development of plasma furnaces.[38] This furnace is basically an electric arc furnace in which carbon electrodes are replaced by metallic electrodes and the electric arcs by plasma arcs.[39] An essential difference in design is the installation of plasma torches in the wall of the furnace, rather than the roof as with carbon electrodes. A plasma furnace used for the production of ferrochromium can be used to produce ferromanganese or other ferroalloys.

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[38] Charles River Associates, *Processing Capacity for Critical Materials*, contractor study prepared for the Office of Technology Assessment, January 1984.

[39] A plasma is a gas of sufficiently high energy content that many of its molecules split into atoms, which then become ionized and electrically conducting. Such a gas can develop and deliver heat as high as 20,000° C. Fossil fuels, on the other hand, limit combustion processes to 2,000° C. See "The Promise of Plasma," 33 *Metal Producing*, February 1984.

The major advantages claimed for the plasma furnace process are: increased economy due to longer life electrodes, fewer environmental problems (e.g., less dust and waste gas are generated, noise level is extremely low), reduced cost of charge material (e.g., use of small particle—"fines"—feed material rather than lumps, eliminating the need for preliminary processes to compact such material, and fine coal rather than more expensive coke), higher product quality (e.g., a lower carbon content), and increased product yield due to lower losses into the waste material.

In the production of ferroalloys, the plasma furnace can either be used for the reduction of ore (as in the submerged arc furnace) or for melting metallic fines. Such a melting operation has been installed by Voest-Alpine of Austria at Samancor (a major manganese ore and ferroalloy producer) in South Africa. Middelburg Steel & Alloys, a major ferrochromium producer in South Africa, has been investigating plasma furnace technology for a number of years and in late 1983 installed a Swedish-designed 20 megawatt (MW) reduction furnace at its plant in Krugersdorp. This is the first commercial application of plasma technology in the ferroalloys field,[40] and Middelburg expects to take 2 years to evaluate the efficiency of the operation before committing to a conversion of its other furnaces (which could result in a doubling of its output capacity) to plasma operation. South Africa appears to be in an excellent position to adopt the plasma technology since its chromite ores tend to break up into fine material, its coal is generally of the lower grade applicable, and electric power is the main energy source. Plasma technology does not yet appear to be able to compete in areas where fossil fuel is available.

Relative to Western Europe, South Africa and the Soviet Union, the United States has seen little activity in plasma technology for process metallurgy (reduction). Westinghouse is one U.S. firm involved in developing the technology, especially the initial torch systems which were a spinoff of the U.S. space program.[41] Foster Wheeler Corp. holds a U.S. license for European plasma furnaces and was involved in setting up the Middelburg furnace. Its estimates have shown that capital costs for the system would be 40 percent less than for a conventional electric arc furnace and operating costs, about 25 percent lower.[42] A major inhibiting factor to U.S. interest in plasma technology is the relatively high cost of electrical power compared with fossil fuel in most parts of the country.[43] However, since ferroalloy processing is an electric power consumer, plasma technology has the potential to be economically viable in this particular application.

Plasma arc reduction processes have occasioned a good deal of interest, but they have yet to be proven in full scale for ferroalloy production. It is not known, for instance, if they can compete with submerged arc furnaces on the basis of energy consumed per ton of ferroalloy produced. They would seem to merit attention, however, if the high-intensity heat source used would permit economical operation of smaller scale units (as compared with the large, 50 MW, submerged arc furnaces). Small-scale, adaptable units could provide flexible production capacity for a new, lean domestic ferroalloy industry.

Chromium Metal

Aluminothermic, carbothermic, and electrolytic processes are used to produce metallic chromium. Each process results in a different quality of product, which determines its possible value to industry. Electrolytic chromium is the purest and used in the most demanding applications. The most widely used method is the aluminothermic (A-T) process. The same equipment can be used to produce other alloys —e.g., ferrovanadium, ferrocolumbium, or ferromolybdenum—providing a wide range of furnace flexibility, but also making it difficult to estimate total aluminothermic capacity.

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[40] SKF Steel of Stockholm announced in June 1984 intentions of building a 78,000-tonne per year ferrochromium plant in southern Sweden using plasma technology. Overall savings of SKF's Plasmachrome process compared to costs of conventional ferrochromium production in Sweden has been estimated at 15 to 20 percent.

[41] K. J. Reid, "Plasma Tech Potential Best in High-Value Goods," *American Metal Market*, May 15, 1984, p. 22. Excerpts from a speech "Plasma Metallurgy in the 80s" given at an international symposium—Mintek 50—in Johannesburg, South Africa, in April 1984.

[42] Charles River Associates, op. cit., p. 78.

[43] Reid, op. cit., p. 22.

The A-T process is relatively simple. High-purity aluminum powder is mixed with Cr_2O_3, charged into a reaction vessel, and ignited. The reaction of aluminum and oxygen produces chromium metal and a slag that contains the oxidized aluminum. The metal is separated from the slag, cooled rapidly, and crushed to specified sizes for sale.

Two products are made by the A-T process. One, known as Chrome 99, is suitable for processes using open vessels in contact with air, but residual oxygen and nitrogen in Chrome 99 limit its use to less demanding end-use applications. The other product, called vacuum melting grade (for use in vacuum furnaces), is produced with excess aluminum to drive down the levels of oxygen. This high purity grade is interchangeable with electrolytic chromium in all but the most stressful applications, e.g., the rotating hot sections of the jet engine.

The A-T process requires high-purity chromic oxide as feed material. This chromic oxide is produced by roasting chromite. Care must be taken during this process to minimize the sulfur, oxygen, and nitrogen content of the end product. Producing this oxide is the capital-intensive phase of chromium metal production.

Another chromium product, Chrome 98, also uses Cr_2O_3 as the input material. Carbon is mixed with the oxide to form briquettes, which are then heated in a vacuum furnace at close to the melting point for several days. The carbon and oxygen form carbon monoxide gas, which leaves behind briquettes of chromium metal. The vacuum furnaces used for this carbothermic process are used for the production of other alloys (e.g., low-carbon ferrochromium) so that total production capacity is difficult to measure. Chrome 98 competes with A-T chromium for use in superalloys.

Chromium metal of the highest purity, consumed in the most demanding superalloy applications, is produced by the electrolytic method. This process, based on developments by the U.S. Bureau of Mines in the 1950s, uses ferrochromium as a feed material. Chemical processing removes the iron content of the ferrochromium, and this "chrom alum" (chromium aluminum sulfate) is then dissolved in water to provide the feed for electrolytic cells. Chromium, deposited on cathodes, is periodically removed. This product is sold as regular grade (99.1 percent chromium) or further purified.

Production Capacity and Distribution

The worldwide distribution of production capacity for ferrochromium and chromium metal is shown in tables 5-14 and 5-15. In 1979, the United States had more than 225,000 tonnes (205,000 tons) of ferrochromium capacity among seven firms. Of the six firms now credited with capacity, only two were operating in 1983, functioning at low levels of production or only intermittently. Early in 1984, temporary respite was provided to one bankrupt firm with the award of a contract from the General Services Administration to upgrade 121,173 tons of chromite in the national defense stockpile to ferrochromium. Table 5-16 shows the increasing U.S. reliance over the past decade on imports of both chromium ferroalloys and metal.

In the past, the West's supply of chromic oxide, the precursor for aluminothermic chromium metal production, was supplied almost entirely by a single firm, the British Chrome & Chemical Co., which has an annual capacity of 12,700 tonnes of chromic oxide. In 1982, however, a subsidiary of the British firm, the American Chrome & Chemical Co., began operating a plant in Texas that produces chromic oxide, along with various chromium chemicals. Shieldalloy Corp. has been producing chromic oxide in the United States, but has used it for internal consumption in the production of A-T metal. It has an annual output capacity of 1,400 tons of chromium metal, with the possibility of expanding capacity to 1,800 tons, if equipment normally used in the production of

Table 5-14.—Ferrochromium Capacity, 1979 (in tonnes)

Country	Charge chrome	High carbon	Medium carbon	Low carbon	Ferro-silico
Brazil	90,000	—	—	—	—
Canada	50,000	—	—	—	—
Finland	50,000	—	—	—	—
France	—	—	—	—	2,000
West Germany	*	*	*	*	35,000
India	10,000+	*	*	5,000+	1,000
Italy	—	40,000 (incl. charge)	—	15,000	—
Japan	172,000	344,100	12,000	106,000	81,400
Mexico	—	—	—	6,000	—
Norway	—	20,000	18,000	—	—
Philippines	—	*	*	*	—
South Africa	270,000	30,000	—	10,000	55,000
Spain	—	28,000	—	10,000	—
Sweden	—	240,000	—	33,000	53,000
Turkey	—	50,000	—	15,000	—
United States	*	136,000+	*	36,000+	53,000+
Yugoslavia	—	68,000	—	15,000	5,500
Total	642,700+	956,100+	30,000	251,300+	285,900+

*—Capacity not available.

SOURCE: Charles River Associates, *Processing Capacity for Critical Materials*, OTA contract report, January 1984.

Table 5-15.—Production Capacities for Chromium Metal in the Non-Communist Countries—1981 (tonnes per year)

Country	Electrolytic	Aluminothermic[a]
France		900-1000
Japan	3,000-4,000	300-1,000
West Germany[b]		600,1,200
Luxembourg		0- 500
Great Britain		2,000-4,000
United States	2,800-3,000	0-1,800

[a] A-T capacity is difficult to estimate since some facilities that are used for the production of other alloys can be used for the production of A-T chromium. The wide range of capacity estimates reflects this difficulty.

[b] There is an additional "captive" producer of A-T chromium in West Germany. Its substantial production is sold directly to two or three companies within West Germany.

SOURCE: Charles River Associates, *Processing Capacity for Critical Materials*, OTA contract report, January 1984.

Table 5-16.—Chromium Ferroalloys and Metal: Imports and Consumption (gross weight, short tons)

	Ferrochromium	Metal[a]
1971:		
Imports	85,187	NA
Consumption	253,193	NA
Imports as percent of consumption	34	—
1974:		
Imports	161,573	1,960
Consumption	472,379	5,479
Imports as percent of consumption	34	36
1980:		
Imports	297,218	4,075
Consumption	388,639	5,635
Imports as percent of consumption	76	72

[a] Metal import data include unwrought metal, waste, and scrap.
NA—Not available.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook*, vol. 1, 1971, 1974, and 1980.

other alloys is employed. In addition, Elkem Metals, which produces Chrome 98 at its plant in Marietta, OH, offers variable capacity because it uses its vacuum furnaces for other products, e.g., vanadium carbide and low-carbon ferrochromium. But briquetting equipment for preparing the furnace feed material limits production to 1,400 tonnes (1,300 tons) of chromium metal per year. A small investment in additional briquetting equipment could easily double output.

Western production of electrolytic chromium metal comes from two plants, one each in Japan and the United States. Toyo Soda has a capacity of 4,000 tonnes (3,600 tons) per year, and Elkem has a 2,800-tonne capacity (2,600 tons). Plans to expand capacity to 4,500 tonnes at Elkem were considered but shelved owing to lack of prospective markets.

The United States still has domestic capacity for all types of ferrochromium products, although "practical" (in operating condition) capacity no longer covers its needs. For instance, estimated practical capacity (1984-85) for high-carbon ferrochromium is placed at 130,000 tonnes (118,000 tons),[44] while 1982 consumption totaled 215,000 tons.[45] Imports are expected to continue to erode U.S. production capacity. Firms that appear to be able to remain viable—e.g., Globe Metallurgical Division of Interlake, Inc.—have small, flexible furnaces which can handle special orders and produce premium grades. In terms of chromium metal production, the United States has the ability to handle all stages of both the electrolytic and aluminothermic processes and produce a substantial portion of domestic needs.

Cobalt Production and Processing

State-controlled mining operations produce more than 90 percent of the world's cobalt supply. The industry is dominated by one such African producer, Zaire, which directly supplies nearly 40 percent of U.S. imports. Unlike the other first-tier strategic materials, the number of producer countries has grown in the past 20 years; and these four countries now hold 9 percent of overall output. In addition, a number of cobalt-containing ore deposits—including some in the United States—have been evaluated in the past decade, but all await improved prospects for primary ores and/or cobalt before any operations will be considered.

Cobalt minerals are oxides, sulfides, or arsenides, and they occur in a number of geological environments. The majority of the world's cobalt production comes from a particular geologic combination (stratabound copper deposits associated with sedimentary rock) that has only been found in Zambia and Zaire. Other geological types in which cobalt is located are laterite, hypogene, and hydrothermal deposits. Hypogene deposits are formed during the crystallization of molten rock in which minerals separate and accumulate. Hydrothermal deposits are formed when water containing metals circulates through rocks, solidifying along fractures to produce vein deposits. The principal product derived from cobalt-bearing laterites is nickel in combination with iron; from hypogenes, nickel, and/or copper.

Cobalt is only a secondary product of current mining operations; therefore, its mining and refining is tied to the primary metals nickel and copper. Thus, normal market fluctuations for cobalt do not usually directly influence decisions to alter production rates. Only two countries have had the capability to produce cobalt as a primary product: Zaire, partly because of its high cobalt content ores (0.35 percent); and Morocco, whose cobalt arsenide ores were mined until 1983. For other producers, increasing cobalt production in the absence of increased demand for copper or nickel means either bearing the cost of stockpiling copper or nickel or running a risk of depressing prices by creating an oversupply in those markets.

Although 12 countries reported mine production of cobalt in 1982, Zaire supplied 45 percent of the world's total output (table 5-17). Zambia contributed another 13 percent. These two African countries are the major sources of cobalt for the free world market, the principal consumers being the United States, Western Europe, and Asia. The United States is dependent on imports for all of its primary cobalt needs. (Eight percent of consumption in 1982 was provided by the recycling of purchased scrap.) The Eastern bloc's cobalt needs are supplied by the Soviet Union and Cuba. Little cobalt is consumed by producer countries, except the Soviet Union.

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[44] Charles River Associates, op. cit., p. 58.

[45] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982*, vol. 1, p. 205.

Table 5-17.—World Cobalt Reserves and Production by Country (million pounds of contained cobalt)

Producer country	Reserves	Average grade percent	Production[a] 1982	Percent of world production
Australia	50	0.10	4.8	9
Botswana	20	0.06	0.6	1
Canada	100	0.07	3.3	6
Finland	50	0.20	2.2	4
Morocco[b]	0	1.20	1.5	3
New Caledonia	500	0.05	1.1	2
Philippines	300	0.08	1.1	2
South Africa	40	NA	NA	—
Soviet Union	300	NA	5.2	9
Zaire	3,000	0.35	24.9	45
Zambia	800	0.25	7.2	13
Subtotal	5,160		51.9	94
Others	840		3.4	6
Total	6,000		55.3	100

[a] Mine output.
[b] Operations suspended in December 1982.
NA—Not available.

SOURCE: U.S. Department of the Interior, Bureau of Mines. Reserve base: *Mineral Commodity Profile 1983: Cobalt.* Production: *Minerals Yearbook 1982*, vol. 1, p. 256.

Foreign Production of Cobalt

The cobalt industry is divided into two groups: vertically integrated firms, which mine ores and process them into cobalt products, and mine producers, which sell semiprocessed ores to refiners. Mining is singly controlled in each producer country, except in Canada, Australia, and South Africa. As table 5-18 shows, a tangle of multi-national firms produce cobalt. U.S. firms have interests in Australia (Freeport and, indirectly, Asarco), Botswana (Amax), Canada (Newmont Mines and Superior Oil), the Philippines (indirectly, Superior Oil, through Sherritt Gordon), and Zambia (Amax).

Cobalt flows worldwide in a number of forms until final products such as metal (electrolytic) cathodes and powder, cobalt salts, and oxides are produced for sale to industrial users. Even within integrated firms, intermediate products are often shipped from the mining country elsewhere for final processing. However, there is a growing trend toward complete processing in the country of origin.

In an emergency, one advantage of vertically integrated processing in the producing country is that final cobalt products—principally pure metal—can be air shipped at no great increase in cost. Intermediate products, on the other hand, have few metal units per pound, and shipping them other than by sea is costly. During the Shaba uprising in Zaire in 1978 and 1979, air transportation proved to be a successful export method.

Because of cobalt's varied and complex processing flows (see the following section on cobalt processing), mine production cannot be discussed independently from final processing. Cobalt production and import data often refer to both the mine producer and the downstream processing countries. When integrated mine producers and independent refiners are both considered, the world's sources of refined cobalt products appear to be diverse, although Zaire still dominates. As table 5-19 indicates, the flow of semiprocessed ores is toward the consuming nations. Zaire, Zambia, and Finland have integrated firms which can completely process their ores into cobalt cathode and powder forms. South Africa now exports both cobalt chemicals (sulfate) and metal powders. Some South African intermediates, however, are still shipped to England and Norway for processing. Canada's Inco now has the capability to produce metal from its ores but maintains the option to ship intermediates to

Table 5-18.—Cobalt Mining Industry by Country

		Ownership		
Country	Major firms	Sector	Major holders[a]	Primary national identity
Australia	Queensland Nickel Pty. Ltd	Private	Metals Exploration (50)	Local
		Private	Freeport[b] (50)	U.S.
	Western Mining Corp. Ltd.	Private	WM Corp. Holdings (100)	Local
	Agnew Mining Co. Pty. Ltd.	Private	Seltrust Mining (60)	Local
		Private	Mount Isa Mines[b] (40)	Local
Botswana	Botswana RST Ltd.	Private	Amax (30)	U.S.
		Private	AngloAmer (30)	South Africa/U.K.
		Private	various (40)	Local
	Operated by BCL Ltd.	Private	Botswana RST (85)	(see above)
		Government	(15)	Local
Canada	Inco Ltd.	Private	[d]	Canada
	Falconbridge Ltd.	Private	McIntyre Mines[e] (40)	Canada
Finland	Outokumpu Oy	Government	(81)	Local
		Private	(balance)	Local
Morocco[f]	Campagnie de Tifnout Tiranimine (CTT)	Private/ government	Omnium (81)	French/ Local
New Caledonia	Societe le Nickel (SLN)	Private	Imetal (15)	French
		Government	SNEA[g] (15)	French
		Government	ERAP (70)	French
Philippines	Marinduque Mining and Industrial Corp.	Government	(87)	Local
		Private	Sheritt Gordon (10)	Canada
South Africa[h]	Rustenberg Platinum Mines Ltd.	Private	JCI (33)	Local
		Private	AngloAmer (24)	Local
		Private	Lydenburg (24)	Local
	Impala Platinum Holdings Ltd.	Private	Gencor (56)	Local
Zaire	Generale des Carrieres et des Mines (Gecamines)	Government	(100)	Local
Zambia	Zambia Consolidated Copper Mines Ltd.	Government	ZIMCO (60)	Local
		Private	Zambia Copper Investment (27)[i]	South Africa/U.K.
		Private	RST International (7)	Local

[a] With approximate percentage of control, if available.

[b] A wholly owned subsidiary of Freeport McMoran Inc. (U.S.).

[c] A subsidiary of MIM Holdings which is (49%) owned by Asarco Inc.

[d] The largest single-shareholder block of Inco stock is 4 percent.

[e] Falconbridge is 32.7 percent owned by Superior Oil through direct equity and its controlling interest in Mylntyre.

[f] Not in production since December 1982.

[g] SNEA is 67 percent owned by ERAP-Entreprise de Recherches et d'Activites Petrolieres, giving ERAP about 80 percent control of SLN.

[h] There are six finance houses (the "Groups") which dominate the South African industry: The Anglo American Corp. of S.A. Ltd. (AngloAmer); Gold Fields of S.A. Ltd.; General Mining Union Corp. Ltd. (Gencor); Rand Mines/Barlow Rand; Johannesburg Consolidated Investment Co. Ltd. (JCI); and Anglo-Transvaal Consolidated Investment Co. Ltd. (AngloTC).

[i] Owned by Anglo American.

SOURCES: E&MJ *1983 International Directory of Mining;* Bureau of Mines, *Mineral Commodity Profile 1983: Cobalt*; Office of Technology Assessment.

its plant in Wales, where cobalt salts are produced. Falconbridge exports processed ore from Canada to its plant in Norway for the production of cathodes.

Firms in Botswana, Australia, New Caledonia, and the Philippines mine and smelt their cores. This intermediate product (matte) is traded to refiners for final processing. Two Japanese firms refine intermediates from the Philippines and Australia. The resulting cobalt cathodes are either consumed in Japan or exported. Amax, the sole U.S. cobalt refiner, currently holds contracts to receive matte from one producer in Australia and from its own operations in Botswana. Output from the major Australian producer, Western Mining, is shipped to Sherritt Gordon's refinery in Canada for processing into cobalt powder. New Caledonia's small output is processed into cobalt salts by Metaux Speciaux in France.

Four of today's producer countries, shown in table 5-20, have initiated production since 1960, causing a redistribution of market shares despite the commanding hold on the market

Table 5-19.—World Refined Cobalt Production—1982, by Country (million pounds)

Country[a]	Recovered metal	Percent of total
CANADA	1,730	4
FINLAND	3,218	7
France	11,100	26
West Germany	880	2
Japan	4,282	10
Norway	2,184	5
SOVIET UNION	8,700	20
United Kingdom	1,600	4
United States	1,016	4
ZAIRE	13,200	30
ZAMBIA	5,392	12
ZIMBABWE	110	<1
Total	43,412	100

[a] Upper case indicates refiner is also an ore producer.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982*, vol. 1, p. 256.

that Zaire has maintained. Until the worldwide recession abates and steady economic growth is anticipated by the mining industry, the current producers of cobalt will remain the only sources.

There has been extensive activity since the late 1970s on cobalt-related projects around the world, including in the United States. A number of mining projects are being or have been evaluated, although none appear economic. Foreign projects (table 5-21) reportedly evaluated include Gag Island in Indonesia, Kilembe copper mine in Uganda (processing of copper-cobalt tailings), the Windy-Craggy deposit in Canada, Musongati in Burundi, Ramu River in Papua New Guinea (see the section on chromium in this chapter), and Goro in New Caledonia. Except for the Ramu River project, which depends on chromite and nickel, the economic viability of these projects will be determined by the market for nickel or copper. (U.S. projects are discussed in detail in the next section.)

Albania has contracted for the construction of a nickel and cobalt refinery, which will produce cobalt oxide from domestic nickeliferous[46] ores. (A West German government firm, Saltzgitter Industriebau A.G., and Inco of Canada are involved.) An unconventional source of cobalt is under investigation in Peru, involving concentration and refining of cobalt-bearing tailings from the Marcona Iron Mine.

These projects represent a potential 20 percent increase in supply for world markets under improved economic conditions. Bringing any of them into production, however, would require considerable capital and lead times of several years to develop the necessary infrastructure.

Table 5-20.—Historical Production—Cobalt, 1960-80, by Country (thousand pounds, contained cobalt; percent of world total)

	1960		1965		1970		1975		1980	
Producer country	Production	Percent	Producer	Percent	Producer	Percent	Producer	Percent	Producer	Percent
Botswana	0	0	0	0	0	0	178	<1	498	1
Canada	3,330	10	3,648	10	4,562	9	2,986	5	3,534	5
Finland	0	0	3,292	9	2,800	5	3,090	5	2,282	3
Morocco	2,802	8	4,038	11	1,332	3	4,324	7	1,848	3
New Caledonia	0	0	0	0	0	0	4,528	7	400	1
Philippines	0	0	0	0	0	0	234	<1	2,934	4
South Africa	NA		NA		NA		NA		[a]	
Zaire	18,166	54	18,492	49	30,772	59	30,860	48	34,180	51
Zambia	4,070	12	3,404	9	5,290	10	5,252	8	9,700	14
Soviet Union	[b]		2,800	7	3,400	6	3,900	6	4,960	7
Subtotal	28,400	85	35,874	95	49,178	94	61,324	94	63,856	95
Other	5,000	15	1,760	5	3,400	6	3,600	6	3,620	5
Total	33,400	100	37,634	100	52,578	100	64,924	100	67,476	100

[a] Estimated 475,000 pounds in 1981.
[b] Only Free World reported in 1960.
NA—Data not available.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook*, 1961, 1966, 1971, and 1981.

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[46] Bearing or containing nickel.

Table 5-21.—Potential Foreign Cobalt Sources

	Estimated cobalt content, million pounds		
Site	Production per year	Deposit	Estimated leadtime to production
Gag Island, Indonesia	2.8	400	2 to 3 years
Kilembe, Uganda	NA	784	1 to 3 years
Windy-Craggy, Canada	NA	982	
Musongati, Burundi	NA	160	NA
Ramu River, New Guinea	5.9	NA	+5 years
Goro, New Caledonia	2.0	NA	3.5 to 5 years
Marcona Mine, Peru	4.0	NA	≈2 years
Albania refinery	NA	NA	≈1985

NA—Data not available.

SOURCE: Office of Technology Assessment.

Following is a brief discussion of each major cobalt mine producer's operations and the processing route of the ores. The industry experienced a cutback in mine production and delay in expansion plans because of the 1981-82 worldwide recession. In 1984-85 future prospects have been regarded cautiously.

Australia

Only intermediate cobalt products are produced in Australia. The major producer, Western Mining, is also the third largest nickel producer in the world. For cobalt recovery, the company processes nickel sulfide ores from deposits in western Australia into mixed nickel-cobalt sulfides, which are shipped to Sherritt Gordon in Canada for processing into cobalt powder. Queensland Nickel in northeastern Australia also produces a mixed nickel-cobalt sulfide, but its ores are nickel oxides from laterite deposits. The intermediate product is shipped to Nippon Mining's refinery in Japan under a life-of-mine contract. Agnew Mining's nickel sulfides are smelted by Western Mining in Australia and refined by Amax at Port Nickel in Louisiana. Although a minor world source of cobalt, Agnew is one of Amax's two current sources of cobalt intermediates. Internally, Australian producers rely on rail for transportation between mining, smelting, and exporting phases of production.

Botswana

The two mines in Botswana, Selebi and Pikwe, are operated by BCL Ltd. (15 percent government owned). The smelting furnace at the mining complex had a production peak of 47,000 tonnes of matte (nickel and copper at 38.5 percent each and cobalt at 0.56 percent) or, 479,000 pounds of contained cobalt in 1981. The matte is sent by railroad through South Africa to the port of East London or through Mozambique to Maputo for sea shipment to Amax's refinery in Port Nickel. The South African route is preferred because the loading facilities at East London are more efficient. Botswana RST has been reevaluating its copper-nickel sulfide ore deposits in recent years. Preliminary indications are that the reserves could be increased significantly, but an investment in extensive drilling is needed for confirmation.

Canada

Canada has two integrated mine producers, Falconbridge and Inco, and one independent refiner, Sherritt Gordon. Most of Canada's cobalt deposits are located in the Sudbury area of Ontario and are classified as nickel/copper sulfides. Falconbridge smelts its ores into a mixed metal matte containing nickel, copper, and cobalt (1 percent). This material is then shipped to Falconbridge's refinery in Kristianstad, Norway, where cobalt cathodes are produced. Inco has produced cobalt oxide at its own plants in Port Colborne and Thompson, Canada. Recently, an electrolytic plant with a design capacity of 900 tonnes (1.6 million pounds) of metal per year began operation at Port Colborne to complete domestic proc-

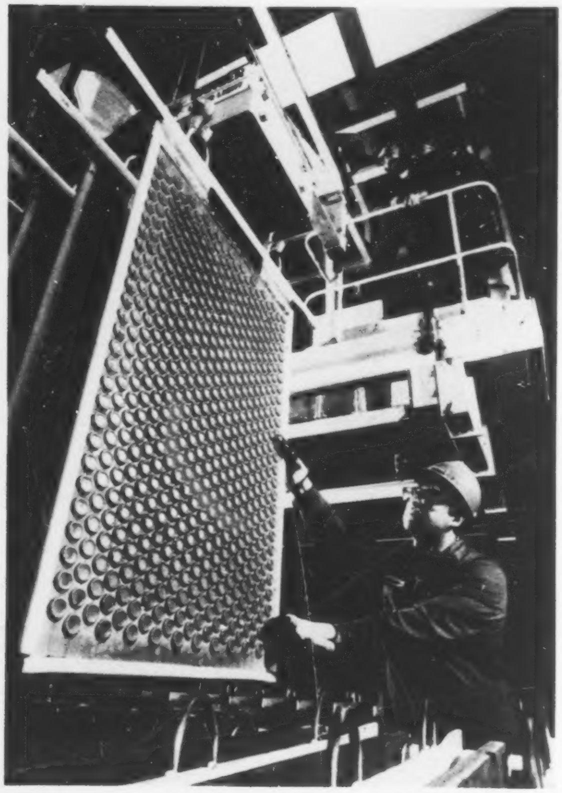

Photo credit: Inco, Ltd.

Cobalt is recovered from nickel and copper ores in the Inco processing plant at Port Colborne, Ontario

essing of the ores. Cobalt oxide will still be produced at Thompson, with some being shipped to Inco's refinery in Wales for final processing. Inco and Falconbridge together normally have the capacity to mine ores containing 9 million pounds of cobalt per year. Inco's smelter has a maximum output capacity of 4 million pounds of cobalt per year. However, world market conditions have reduced actual output by half in the past few years. Sherritt Gordon stated in 1983 that if the price of cobalt rose to $10 per pound (signaling improved markets), the company would triple its output of cobalt powder.[47]

Finland

The integrated firm Outokumpu Oy, Finland's sole producer, derives cobalt from copper sulfide ores containing copper, zinc, and cobalt; the ores are from the firm's Keretti and Vuonos mines in eastern Finland. A cobalt concentrate is subsequently processed at the Kokkola refinery on the west coast. Products include both cobalt powder and salts. Outokumpo has been conducting exploration and process development work (a new concentration technique based on leaching technology) at the Talvivaara deposit near Sotkamo in order to improve the firm's reserve figures and develop a new source of cobalt, as well as nickel, zinc, and copper. Total resources have been estimated at 300 million tons of ore which, with a cobalt grade of 0.02 percent, represents 60,000 tons (120 million pounds) of cobalt. If the processing technique proves feasible, about 10 million tons of ore (containing 4 million pounds of cobalt) could be produced annually.

Morocco

Cobalt production in Morocco was discontinued in December 1982 because declining reserves and increased mining costs made the firm's cobalt production noncompetitive. A better worldwide economic climate could encourage broadening of the reserve base and reopening of the mines. Morocco's ores are cobalt-iron-nickel arsenides, and Morocco is the only world producer for which cobalt has been the primary product. The ores were processed in France by Metaux Speciaux, a subsidiary of Pechiney Ugine Kuhlmann, the state-owned metals group. The oxide and metal products were consumed internally. (Metaux Speciaux now receives cobalt intermediates from SLN in New Caledonia for processing into salts.) Amax considered using Moroccan ores and ores in the tailings at the Uganda Kilembe copper mine as a feed for its U.S. plant. Neither source presents any technical problems, but it is difficult and costly to transport the ores from either spot in northern Africa to the Botswana smelter for initial processing.

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[47] *American Metal Market*, Oct. 27, 1983.

In 1982, the Trade and Development Program of the U.S. International Development Cooperation Agency completed a study of the prospects for Moroccan cobalt production.[48] The study reported that, although the reserves were approaching exhaustion, the potential for discovering new cobalt deposits in the Bou Azzer region (site of the closed mines) was very high, suggesting that extensive geological studies be undertaken.

New Caledonia

Only 8 percent of the cobalt in SLN's ores is recovered because most of its nickel oxide ores are smelted directly into ferronickel. (See discussion of cobalt losses due to ferronickel production in the following processing section.) The cobalt intermediates that are produced by SLN's smelter are processed in France by Metaux Speciaux. Cofremmi, S.A., a firm controlled by Amax, BRGM (France), and Patino N.V. (Netherlands), has studied the feasibility of mining the nickel laterite deposits containing cobalt at Goro, estimating a cobalt output of 1,000 tons (2 million pounds) per year. A deposit at Tiebaghi has been investigated by Amax. Both deposits could be exploited using existing technology, but eventual production from either source will depend on the nickel market.

The Philippines

Some 20 nickel laterite deposits, with varying cobalt content, have been identified in the Philippines, although only one is in production. Marinduque derives cobalt from a large deposit with 0.10 percent cobalt content at Surigao on Nonoc Island. A mixed nickel-copper sulfide is shipped to Japan for refining into cobalt cathodes by Sumitomo Metal Mining. Marinduque planned a cobalt refinery with a rated output of 1,200 tons (2.4 million pounds) per year, but current financial problems have prohibited any action. It is estimated that the plant would take about 18 months to complete.

South Africa

Cobalt from the Union of South Africa is produced from nickel products separated during platinum ore beneficiation. Data on actual cobalt production became available only recently. Production in 1981 has been estimated at 475,000 pounds of recovered cobalt. Two producers, Rustenburg and Impala, are now fully integrated within South Africa. Rustenburg processes nickel mattes into cobalt sulfate at a plant jointly owned with Johnson-Matthey. Impala's mattes are processed into cobalt powder at its refinery at Springs in the Transvaal Province. A third (minor) producer, Western Platinum Ltd., ships mattes to the Falconbridge plant in Norway for processing. (Falconbridge, a Canadian firm, is part owner of Western Platinum.)

Zaire

The copper oxide and mixed oxide-sulfide deposits of Zaire have one of the world's highest concentrations of cobalt (average 0.3 percent). Gecamines (the government mining firm) recovers cobalt after the last step of the copper ores processing. This makes cobalt production relatively inexpensive, but because the operations seek to maximize copper recovery, overall cobalt recovery from the mined ores is only in the 30-percent range. Mine-to-metal cobalt production is integrated at the mining area. Gecamines' two refineries produce cobalt metal cathodes.

Metallurgie Hoboken Overpelt in Belgium has an agreement with Zaire to process refined cobalt into cobalt chemicals and extra-fine powder. During the depressed markets of the past few years, Gecamines has stockpiled cobalt rather than substantially curtail its production rate. Estimates are that, by the end of 1982, Zaire and its sales agents were holding more than 20,000 tonnes (36 million pounds) of cobalt products off the world market. This amount exceeds Zaire's 1980 production rate of 17,090 short tons (34 million pounds).

Zaire was granted $360 million in loans by the International Monetary Fund in 1984 to help compensate for the decrease in export earnings due substantially to the depressed world markets for copper and cobalt. There have been attempts to open additional Zairian sources of cobalt by various consortiums of government and multinational private firms (e.g., Sodimiza and Societe Miniere de Tenke-Fungurume), but they have failed because of market conditions for both copper and cobalt.

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[48] U.S. International Development Cooperation Agency, Trade and Development Program; *Morocco Cobalt Mission*, February 1982.

After the Shaba crisis ended in 1979, Zaire continued to use air transportation for cobalt exports until the price of cobalt dropped dramatically. Land routes from Zaire include a river barge/rail combination west to the port of Matadi and rail routes via South Africa and Tanzania. Negotiations were underway in 1984 to allow Zaire the use of the Mozambique port of Beira.

Zambia

While Zambia produces from the same ore belt as Zaire, Zambia's ores are almost exclusively copper sulfides, and the concentration of both copper and cobalt (0.15 percent) is lower than in Zaire. The overall recovery rate for cobalt is about 25 percent. (The cobalt refinery yield is 75 percent, but only a third of the mined cobalt containing ores are processed for cobalt with the rest going to copper.) Sulfide ore processing requires smelting and separate streams for copper and cobalt rather than the sequential hydrometallurgical extraction process used in Zaire with oxide ores. The end product in Zambia is cobalt cathodes, half of which are of the high purity required for superalloy use.

The major transportation route from Zambia, especially for copper, is via the Tazara Railroad to the port of Dar es Salaam in Tanzania. The railroad was built in the 1970s. with assistance from the Chinese government, to reduce black southern Africa's dependence on rail routes through South Africa. It has been continually plagued with equipment and maintenance problems, reducing its reliability. China agreed to extend the grace period for repayment of the railway's debt, freeing up funds for repairs and for purchase of additional rolling stock. Several Western European nations have agreed to assist the rehabilitation effort. The port of Dar es Salaam tends to be a bottleneck causing extreme delays in shipments.

Potential Sources

The first of the following potential sources of cobalt is of particular interest because it is located close by in Peru and because little development would be required to produce cobalt. The time-consuming ground work has been completed for the second project, and it awaits economic viability.

Peru/Marcona Iron Mine

It has long been known that the iron sulfide (pyrite) tailings from operation of the Peru/Marcona iron mine contain cobalt. The Trade and Development Program (TDP) studied this project in 1982[40] at the request of Hierro-Peru, the Peruvian government iron mining concern, and estimated that at an iron mining rate of 7.2 million tons per year, 2,079 tons (4.2 million pounds) of cobalt could be recovered annually from the pyrite tailings. (In 1981, nearly 7.5 million tons of crude ore were mined, although the mine has an annual capacity of 15 million tons.) Additional cobalt is contained in the tailings generated over the lifetime of the mine's operation. The TDP report proposed that the cobalt ore be prepared for use in a U.S. refinery, such as the Amax refinery in Louisiana or one of Hall Chemical's plants. An evaluation was underway in 1984, funded by the TDP, to identify the required processing steps, the necessary infrastructure, and the capital requirements. This cobalt source might provide one of the quickest new supplies, given any disruption in the normal market, because the iron mining operation and most of the infrastructure required are already in place. Deepwater port loading facilities are available nearby.

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[40] U.S. International Development Cooperation Agency, Trade and Development Program, *The Marcona Iron Mine: A Potential New Source of Cobalt in Peru*, November 1982.

Indonesia/Gag Island

After 10 years and a $50 million investment, further investigation on the nickel laterite project at Gag Island, Indonesia, was halted in 1981 by P.T. Pacific Nikkel Indonesia. The partnership of U.S. Steel, Amoco Minerals, and Ijmuiden Hoogovens BV of The Netherlands was subsequently liquidated. The reasons given for abandoning the project were the depressed state of the nickel and cobalt markets and the uncertainty of the future, along with interference by the Indonesian government. A production rate of 60,000 tons of nickel and 1,400 tons (2.8 million pounds) of cobalt for the first 10 years of operation had been projected.

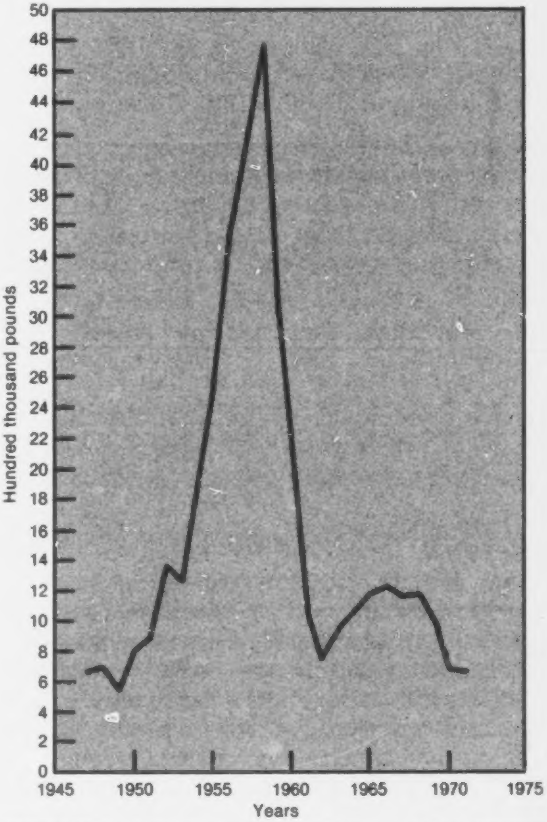
(See also the Ramu River, Papua New Guinea, project discussion in the chromium section.)

Domestic Production of Cobalt

Currently, cobalt is not produced from domestic mines, but this has not always been the case. U.S. mine production (fig. 5-3) reached a high point in 1958, when about 4.8 million pounds of contained cobalt were produced. (U.S. consumption of cobalt in 1958 was 7.5 million pounds.) In the 1948-1962 period, a total of approximately 14 million pounds were acquired by the government through stockpile purchases and Defense Production Act subsidies. Federal purchases included about 6 million pounds of cobalt from the Blackbird Mine in Idaho, and about 2.9 million pounds from mines in the Missouri Lead Belt (including the Madison Mine). There has been no production from these mines since the Federal purchase contracts expired more than two decades ago. During the period 1940-72, approximately 500,000 pounds of cobalt were produced each year from iron ore pyrite concentrates taken from Pennsylvania's Cornwall Mine.[50]

Since 1980, Federal subsidies for domestic cobalt production have again been proposed as an alternative to stockpiling. These proposals are discussed later in this section, and also in chapter 8.

Figure 5-3.—Total U.S. Cobalt Production, 1945-71 (cobalt content of mined ores)



SOURCE: William S. Kirk, Commodity Specialist, Bureau of Mines, Department of the Interior, 1984.

Domestic deposits that may yield cobalt to meet national needs today are the Blackbird deposits, the Madison Mine of Missouri and associated cobalt in the Missouri Lead Belt, the Gasquet Mountain project in California, and in the Duluth Gabbro of Minnesota. Older, smaller mines primarily located in the Eastern United States, such as Pennsylvania's Cornwall Mine, are not considered potentially economic sources by the Bureau of Mines.

Fluctuating metal prices have made it difficult to assess domestic cobalt development projects. In 1981, spokesmen for the Blackbird, Madison, and Gasquet Mountain projects all stated that sustained market prices of from $20 to $25 per pound would be required to warrant production.[51] At that time, the market price for cobalt was $15 per pound, by 1983 it had dropped to $5 to $6 per pound, and in 1984 was being quoted at $10 to $12 per pound.

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[50] The history of domestic cobalt production, through 1968, is discussed in James C. Burrows, *Cobalt: An Industry Analysis,"* Charles River Associates Research Study (Lexington, MA: Heath Lexington Books, 1971), pp. 103-113 and 185-189.

Although large deposits containing amounts of cobalt too small to be mined for cobalt alone occur throughout the world, the Madison and Blackbird deposits could—according to their proponents—support the mining of cobalt as a primary ore. Other domestic cobalt resources can be produced only as byproducts and would therefore be unlikely to respond solely to changes in the price of cobalt. The California-Oregon laterite deposits are primarily nickel, but the Gasquet Mountain project in northern California is dependent on nickel, chromium, and cobalt prices for success. The Missouri lead and zinc mines may have only a small relative incremental cost for producing small amounts of cobalt, but production at these mines is dependent on the base metals market. Moreover, cobalt recovery from these Missouri ores may require changes in lead and zinc processing practices and, in some cases, in end use standards. With present technologies, it is thought that increased cobalt recovery would result in higher iron concentration in recovered lead and zinc, which may not be satisfactory for consumers of lead-zinc products.[52]

The development of deposits in part of the Duluth Gabbro depends on copper and nickel markets. At copper and nickel prices at least double 1983 levels, these Minnesota deposits could become an attractive venture. Values of precious metals may also contribute to prospects for development of this area. However, the considerable excess production capacity of U.S. copper mines and of Canadian copper and nickel operations dampen prospects for production from these deposits.

Given the proper economic incentives (sustained, higher market prices for primary metals and/or Government subsidies), domestic sources (table 5-22) that have seen recent commercial activity could annually supply 7.7 million pounds of cobalt. Another 800,000 to 2 million pounds per year might be recovered from the Duluth copper-nickel sulfide deposits. (U.S. consumption of cobalt in 1982 totaled about 10 million pounds.) At current estimated resource levels, production from these deposits would range from 12 to 25 years.[53]

Blackbird Mine

The Blackbird Mine is located in the Salmon River Mountains of Lemhi County, ID. The Caldera Co. acquired claims to the Blackbird District in 1943 after investigations by the Bureau of Mines revealed the presence of commercially feasible deposits of cobalt. Production began in 1950 with subsidies under the DPA running from 1952 through 1959, when production ceased.[54]

Blackbird is now managed by Noranda Mining of Canada, which has proposed reopening the Blackbird Mine and concentrator to produce 1,200 tons of copper-cobalt ore daily.[55] A final environmental impact statement (EIS) was published in 1982. Permits currently allow production of 300 tons daily for a "pilot" operation. However, in 1981 Noranda began laying off employees, and when the final EIS was issued, only a few workers were still on site. The project is on hold awaiting improvement in cobalt demand and prices. The company has sealed off the mine at the 6,850-foot level, and the mine is filling with water.

Ore reserves at Blackbird are now given at 7.5 million tons of 0.72 percent cobalt (108 million pounds of contained cobalt) with 1.4 percent copper and 0.01 percent gold. The esti-

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[51] Hearings before the U.S. Senate, Committee on Banking, Housing, and Urban Affairs, Oct. 26, 1981, p. 145. Noranda Mining, the Blackbird Mine owners, now believe that a sustained cobalt price of $16 per pound would make it feasible to bring the mine into production due to improved mine planning and the discovery of higher grade ores. The other mine owners have not revised their 1981 figures.

[52] Silverman, et al., op. cit.

[53] Production levels at Blackbird, Madison, and Gasquet Mountain were stated in testimony during U.S. Senate hearings before the Committee on Banking, Housing, and Urban Affairs on Oct. 26, 1981. They were also confirmed to OTA in telephone conversations with each mining firm in July 1984. Data for Duluth Gabbro is taken from the Minnesota study cited in note 67.

[54] Burrows, op. cit., p. 187.

[55] Silverman, et al., op. cit., p. 67.

Table 5-22.—Potential U.S. Cobalt Production

Resource/Mine	Estimated annual production capacity (million pounds of recovered cobalt)	Estimated minelife (years)	Production dependent on
Blackbird Mine Idaho	3.7	20	Cobalt price of about $16 per pound (1984)[a]
Madison Mine Missouri	2	20	Cobalt price of about $25 (1981)[a]
Missouri Lead Belt (tailings)	2	?	Cobalt price of about $20-25 (1984)[a]
Gasquet Mountain California	2	18	Cobalt price of about $20 (1981)[a] plus Nickel $2 to $3 per pound Chromite $40 per ton
Duluth Gabbro Minnesota	0.8-2	25	Copper, $1.50 per pound Nickel, $4.00 (1975 data converted to January 1983 dollars)

[a] Year of estimate.

SOURCE: Blackbird—Noranda Mining, July 1984.
Madison—Anchutz Mining, July 1984.
Missouri Lead Belt—Amax estimates, July 1984.
Gasquet Mountain—California Nickel Corp., July 1984.
Duluth Gabbro—State of Minnesota, *Regional Copper-Nickel Study*, 1979.

mated cost of production has declined over the last few years with the discovery of higher grade reserves and improved mine planning, and the mine life has almost doubled to 20 years. An estimate provided to OTA by Noranda holds that about $16 per pound is the price of cobalt needed to promote the development of the project. Should that occur, 3.7 million pounds of cobalt is expected to be recovered per year.[56]

The Blackbird ores contain high levels of arsenic, and past mining operations contaminated streams flowing into the Salmon River drainage. As a condition of reopening the project, Noranda agreed to install a water treatment facility and take other measures to improve and protect water quality. Noranda negotiated a settlement with the Environmental Protection Agency in July 1983 that allowed the company to close the water treatment plant, evidence of the declining commercial interest in this project. The cobalt concentrates from Blackbird also contain a level of selenium which may or may not be a problem in superalloy use. Noranda officials claim that effective techniques to reduce this element to a lower level, if necessary, are available. (The current maximum allowable limit for selenium in jet engine superalloys is 5 parts per million.)[57]

The proposed mining area is surrounded by private and public lands, approximately 6 miles from a wilderness area on National Forest land. Some of the mining claims (not connected with the Blackbird Mine, as proposed) extend into the wilderness area. However, the Act[58] creating the wilderness area made special provisions for exploration for cobalt. No exploration activities have yet been carried out in the special mineral management area, despite tentative approval granted Noranda by the U.S. Forest Service.

Large amounts of cobalt are contained in tailings from previous operations at Blackbird; however, Noranda does not count the tailings in its reserves, and at present is unlikely to exploit them for their mineral content. The firm would thereby avoid incurring responsibility for rectifying water pollution and waste problems caused by past imprudent handling of these mine wastes. The State of Idaho filed a preliminary suit under the Resource Conservation and Reclamation Act against Noranda and previous owners for environmental damage.

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[56] Richard Fiorini, Vice-President and General Manager, Noranda Mining Inc., personal communication, July 1984.

[57] American Society for Metals, *Quality Assessment of National Defense Stockpile Cobalt Inventory*, prepared for the Federal Emergency Management Agency (Metals Park, OH, 1983), p. 26.

[58] Public Law 96-312, The Central Idaho Wilderness Act of 1980, authorized exploration for cobalt in special management zone in the River of No Return Wilderness area near Blackbird Mine.

Madison Mine and Missouri Lead Belt Deposits

Mines in the southeast Missouri lead district produced 5.2 million pounds of cobalt from 1844 to 1961. In 1979, Anschutz Mining acquired the inactive Madison Mine, located near Frederickstown in part of the old Missouri Lead Belt, an area where most of the lead and zinc mines have been depleted. The Madison Mine produced 2.8 million pounds of cobalt from 1954 to 1961, before it was closed. The mine also produced lead, copper, and nickel. The cobalt mineralization is reportedly high enough in one zone in the mine to support cobalt production as a primary ore.

If reopened, the mine could have an estimated annual production of 2 million pounds of cobalt. Recoverable geologic (as opposed to economic) cobalt reserves at the Madison Mine are given as 37 million pounds (in 5.6 million tons of ore and 3.4 million tons of existing tailings).[59] The depressed world price of cobalt and lack of Government action on proposed price supports under the Defense Production Act have led Anschutz to postpone opening the mine. In 1981, company officials said an estimated guaranteed price of about $25 per pound would be necessary to promote production from Madison.[60] Economic studies have not been revised to reflect any changes in mining costs since then.

Cobalt in the Madison Mine is a sulfide mineral. Anschutz Mining has reportedly found a previously unrecognized cobalt ore body that does not contain the lead and zinc customarily associated with cobalt deposits in the Missouri Lead Belt. This discovery could prove to be significant worldwide in identifying an additional geologic environment for cobalt occurrences.

An underground and surface mining operation has been proposed for the Madison Mine including a smelter to refine its own ores and process existing tailings from previous mining periods, as well as the tailings from other lead belt producers. Perhaps 300,000 to 400,000 pounds of cobalt is recoverable from these tailings given the current technologies used by the region's lead mines to produce lead and zinc from their ores.[61] Up to 1.5 million pounds might be available, given changes in lead and zinc recovery practices.

Another analysis[62] of extracting cobalt from the byproducts of lead-zinc mining in Missouri estimates that 2 million pounds could be produced per year, based on the recovery of 65 percent of the cobalt content in currently mined ores. Capital requirements would be in the range of $40 million to $65 million to install equipment to treat the raw materials (mill tailings, smelter slags, mattes, copper concentrates and copper-cobalt cakes). This is substantially less than would be required to finance a new mining venture and would likely yield an acceptable return if the price of cobalt were $20 to $25 and if raw materials from several firms operating in the Lead Belt were pooled to provide economies of scale. Successful implementation would also require work, in addition to that already done by the Bureau of Mines Rolla Research Center, on technologies to recover cobalt from mill tailings and blast furnace slag.

Gasquet Mountain Project

Cobalt resources are contained in nickel laterite deposits in northern California and Oregon.

California Nickel Corp., a wholly owned subsidiary of Ni-Cal Development Ltd. of Canada, has proposed development of the Gasquet Mountain mine on unpatented mining claims it controls in the Six Rivers National Forest in northern California. The mine, along with associated milling and processing facilities, as proposed would annually produce 2 million pounds of cobalt (cathode), 19.4 million pounds of nickel (cathode), 50,000 tons of chromite concentrate (42 to 43 percent chromic oxide), and 100,000 tons of magnesium oxide. Mine life has been calculated at approximately 18 years.[63]

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[59] John Spisak, Vice-President for Operations for Anchutz Mining, personal communication, July 1984.

[60] U.S. Senate, Committee on Banking, Housing, and Urban Affairs, hearings, Oct. 26, 1981, p. 145.

[61] Silverman, et al., op. cit., p. 111.

[62] This preliminary analysis was provided to OTA by Amax, which has extensive holdings in the Missouri Lead Belt from which it produces lead and zinc.

California Nickel has sought production subsidies from the government for the operation,[64] one of several factors that have made the proposal controversial. Viability of the project hinges on the economics of multiple (cobalt, nickel, chromium) metal production and processing, on successful mitigation of several adverse environmental impacts, and on demonstration that mine areas can be reclaimed. A draft EIS was published in March 1983, but the project appears to be in suspension.

Based on a Kaiser Engineers' mine feasibility study for the project, estimated total ore reserves at Gasquet Mountain are 23.6 million tons (16.0 million of which are proven reserves with grade of 0.75 percent nickel, 0.07 percent cobalt, and 2 percent chromium). Kaiser estimated annual ore production of 1.32 million tons would be required to generate 2 million pounds of cobalt per year.

Kaiser also examined several prospective processing techniques. It concluded that with the use of a high-pressure acid leach process (a well-established 20-year old hydrometallurgical technology) maximum extraction of both nickel and cobalt would occur. In addition, use of this process would make it possible to recover most of the chromite in the ores using existing gravity concentration methods and, "might yield another commercial product."[65]

The operation would be a surface mine operating at the crest of 2,000- to 3,000-foot mountains. The mineralization of the Gasquet deposit is shallow, down to about 25 feet; and mining would consist of scooping up the soil with backhaulers. Cost to build the project in 1982 was projected at $300 million.[66]

California Nickel has now split its operations into two separate units. One oversees the mining project itself and the other, Ni-Cal Technology Ltd., is pursuing the development and promotion of a modified acid leach processing technology that was intended for the Gasquet mine. Six patent applications have been filed so far, and Ni-Cal intends to build a pilot plant to test the process on ores from various sources. Marketing of the process is aimed at laterite mining operations in the Pacific rim area. No domestic prospects are in sight.

Duluth Gabbro

The Duluth Gabbro, in northeastern Minnesota, has been suggested as a potential source of cobalt, as well as PGMs. Cobalt production would only be as a byproduct, dependent on the production of copper and nickel. The area contains an estimated recoverable resource of 20 million tonnes of copper, 5 million tonnes of nickel, 80,000 to 90,000 tonnes of cobalt (145 million to 164 million pounds), and lesser amounts of titanium, platinum, gold, and silver.[67]

A Regional Copper-Nickel Study was released by the State of Minnesota in 1979.[68] The study, conducted from 1976 to 1979, assessed the technical aspects of the development of mining activities in the Duluth Gabbro and resultant environmental, economic, and social impacts. Mining schemes were developed with the goal of generating representative models, rather than for predicting or recommending the choices that might actually be made by a company developing a specific ore deposit. It was decided that technology and economic conditions required large-scale operations for Minnesota's low-grade resource to compete in late 1970s markets. Thus, the models provided for a minimum annual production of 100,000 tonnes of metal (85 percent copper and 15 percent nickel). Three hypothetical mine-smelter complexes were considered, one each with an underground, open pit or combination underground/open pit mining operation. Assuming simultaneous development of these three models, an annual production of 254,000 tonnes (231,000 tons) of copper could be generated over a period of approximately 25 years.

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[63] Documents provided to OTA by California-Nickel, March 1983.

[64] U.S. Senate, Committee on Banking, Housing, and Urban Affairs, hearings, Oct. 26, 1981, p. 185.

[65] Kaiser Engineers, *Interim Report for the Gasquet Mountain Project*, March 1982, p. 5-10.

[66] Ibid., p. 18.

[67] Minnesota Environmental Quality Board (State Planning Agency), *The Minnesota Regional Copper-Nickel Study, 1976-1979*, vol. I, Executive Summary, August 1979, p. 10.

[68] Ibid.

A report prepared for OTA estimated potential overall cobalt recovery of 25 to 30 percent from Duluth ores, with significant amounts of the cobalt lost to mill tailings and during refining.[69] For every 100,000 tonnes of copper produced, associated cobalt recovery would be about 400 to 450 tonnes or about 800,000 pounds.[70]

Operation of copper-nickel production at Duluth would be marginally economic at metal prices of $1.50 per pound for copper and $4 per pound for nickel, in January 1983 dollars.[71] (In 1983, the U.S. producer delivered price for copper cathodes averaged 77 cents and the spot price for nickel averaged $2.20.)[72]

Other Domestic Cobalt Deposits

Pennsylvania's Cornwall Mine produced cobalt for many years, yielding 400,000 to 600,000 pounds annually as a byproduct of mining iron ore. From 1940 until operations ceased in 1972, the mine produced 100,000 tonnes (182 million pounds) of cobalt ore. The Gap Nickel Mine in Lancaster County, PA, has 1 million tons of remaining ore at grades of 0.1 to 0.3 percent cobalt. Although these small cobalt deposits are potential resources, there has been no thorough examination of the economic and technical viability of mining them. They have usually been omitted from Minerals Availability System Appraisal studies conducted by the U.S. Bureau of Mines because their probable cobalt yield is not considered significant.[73]

Proposed Federal Subsidies for Domestic Cobalt Production

As is discussed in chapter 8, proposed renewal of Federal support for domestic cobalt production has been the subject of considerable debate in Congress and the Administration. Most of this debate has focused on proposed Federal support for domestic cobalt production, under Title III of the Defense Production Act. (Title III authorizes purchase commitments, loans, and loan guarantees for materials, services, and facilities considered essential for defense needs.) President Reagan, in his April 1982 national materials plan submitted to Congress under the National Materials Policy, Research, and Development Act of 1980, indicated that analyses were ongoing to determine whether DPA incentives might be more cost effective than stockpile purchases in some circumstances.

The great fluctuation in cobalt prices since 1978 in fact has made it very difficult to make cost-benefit comparisons among stockpile/domestic production options, as was made clear in hearings held in early 1983 about an Administration proposal to provide federally guaranteed price supports for domestic cobalt production.[74] In August 1982, the Federal Emergency Management Agency (FEMA) issued a report comparing four alternative combinations of Title III subsidies and stockpile purchases for cobalt—ranging from exclusive reliance on government stockpile purchases on the world market to extensive reliance on a government-guaranteed minimum price to domestic cobalt producers—which might be used to realize the materials availability equivalent of the strategic stockpile goal of 85 million pounds of cobalt.[75]

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[69] Silverman, et al., op. cit., p. 181.

[70] *The Minnesota Regional Copper-Nickel Study*, op. cit., p. 10.

[71] Silverman, et al., op. cit., p. 182. These data are based on conclusions from a 1975 study, *Mineral Beneficiation Studies and an Economic Evaluation of Minnesota Copper-Nickel Deposit From the Duluth Gabbro* by J. E. Lawver, et al., for the U.S. Bureau of Mines.

[72] U.S. Department of the Interior, Bureau of Mines, *Minerals and Materials: A Bimonthly Survey*, December 1983/January 1984, pp. 25 and 29.

[73] Silverman, et al., op. cit.

[74] U.S. Senate, Committee on Banking, Housing, and Urban Affairs, Extension of the Defense Production Act, hearing on Mar. 21, 1983, 98th Cong., 1st sess., Senate Hearing 98-66 (Washington, DC: U.S. Government Printing Office, 1983).

[75] Federal Emergency Management Agency, *Alternative U.S. Policies for Reducing the Effects of a Cobalt Supply Disruption—Net Economic Benefits and Budgetary Costs*, August 1982, as reproduced in its entirety in ibid., pp. 15-100.

For each scenario, cobalt prices, budget expenditures, and overall economic costs were projected over a 10-year period (1981-90) under both a "no disruption" assumption and a peacetime disruption assumption affecting 50 percent of normal U.S. supplies. The disruption was assumed to occur in 1985. Each of these scenarios, which addressed the 1981-90 period, were intended to provide an equal degree of supply security. FEMA recommended, as the most cost-effective option, a so-called "hybrid" alternative entailing a 5-year program of government-stimulated production of 10 million pounds of cobalt annually from domestic mines, supplemented by stockpile purchases of 1.42 million pounds for 10 years. The domestic production would be stimulated through a federally guaranteed minimum price of cobalt of about $15 per pound.

When hearings were held on the FEMA proposal in March 1983, cobalt prices had fallen to about $6 per pound on world markets. The U.S. General Accounting Office (GAO), which testified on the FEMA report,[76] found that FEMA's "stockpile only" analysis in a nondisruption scenario assumed cobalt prices would rise to over $36 per pound by 1990, more than double the price projections made by other government agencies. In its hybrid scenario, FEMA assumed that Federal price guarantees for domestic production would only be necessary for a 5-year period. This would only be the case if FEMA's projected cobalt price is assumed to be accurate. GAO found that, at 1983 prices, buying cobalt on the world market for the stockpile would be far cheaper than subsidizing domestic production.

Another Defense Production Act issue that has received considerable attention concerns a Department of Defense (DOD) proposal for pilot plant production of domestic cobalt in order to evaluate the quality of this cobalt for defense applications. In 1983, the Air Force issued a draft Request For Proposal (RFP) to potential domestic producers concerning such a project. According to DOD, the draft RFP was issued for two reasons: 1) to secure "definitive data through legal contracting procedures for a cost/benefit analysis of domestic cobalt production"; and 2) "to determine if domestically produced cobalt will meet national security requirements."[77] DOD maintains that the issuance of the draft RFP was simply to evaluate the costs and benefits of the proposal, in order to support activities of its DPA Title III steering committee, which has been set up to evaluate candidate DPA projects. However, the cobalt pilot plant became an issue in congressional debate about amendments to the Defense Production Act in April 1984. (The DPA amendments are discussed in chapter 8.)

Domestic Mining and Processing Technology Prospects

Lateritic deposits containing cobalt are suited to open pit mining and to the continuous systems of excavators and conveyor belts that will gradually become more common in steep pits. Open pit mining in harder rock would be practicable in the copper-nickel-cobalt deposits of the Duluth Gabbro, with underground mining at depths involving open stoping and room-and-pillar methods. In the steeper hard-rock bodies of cobalt ore such as at Blackbird, cut-and-fill mining and the new ramp-in-stope system underground methods could be appropriate.

Process technology has been developed for recovering cobalt from the Blackbird and Madison deposits, and preliminary pilot-scale testing has been completed for both properties and byproduct cobalt production from Missouri's lead mines. Commercial facilities have not been designed or tested, however. Ore processing systems could be designed for these deposits, plus Duluth Gabbro, that would allow shipment to the existing Amax Nickel refining plant at Port Nickel for final processing.

The Bureau of Mines has conducted research into reclaiming the cobalt from Missouri lead ores which is currently neglected (an estimated

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[76] Statement of J. Dexter Peach, Director, Resources Community and Economic Division, U.S. General Accounting Office, as reproduced in ibid., pp. 3-6.

[77] As discussed in U.S. Senate, Committee on Banking, Housing, and Urban Affairs, hearing: Reextension of the Defense Production Act, Hearing on S. 1852, Sept. 15, 1983, Senate Hearing 98-400 (Washington, DC: U.S. Government Printing Office, 1983), p. 159.

2.5 million pounds of contained cobalt per year is lost) during lead, zinc, and copper processing.[78] In other research, the Bureau investigated the extraction of cobalt from the liquid which remains after dilute acid solutions have leached copper from its ore. One U.S. copper mine might be able to contribute 1.3 million pounds of cobalt per year through this process, which has not yet been economically evaluated.[79]

Research on Blackbird complex arsenical copper-cobalt ores is attempting to find the basis for less costly extraction technology than currently exists. Investigations have centered on methods for improving hydrometallurgical technology because severe sintering and atmospheric pollution problems occur with an alternative roasting procedure. Selective solvent extraction processes are being compared with conventional precipitation processes for removing iron and recovering cobalt, nickel, and copper from the resultant leach liquids.[80]

A comprehensive plan to recover all of the mineral values in Duluth Gabbro ores (nickel, copper, cobalt, silver, gold, and PGMs), rather than concentrate on the primary metals, has undergone investigation by the Bureau of Mines Twin Cities Research Center in Minnesota. The approach is a combined pyrometallurgical-hydrometallurgical process to recover a maximum amount of the byproduct metals without sacrificing energy or metallurgical efficiency.[81]

Laterite ores containing cobalt could benefit from a commercial hydrometallurgical process developed by Ni-Cal Technology Ltd. as a spin-off of the Gasquet Mountain project in northern California. After separating out chromite from the mined ores, a slurry of the residual nickel-cobalt-iron minerals is leached, producing separate nickel-cobalt sulfide and iron concentrates. Nickel and cobalt are then produced by standard selective precipitation and solvent extraction methods, and further refining is accomplished by electrowinning.

Domestic and Foreign Cobalt Processing

The primary industrial uses of cobalt are in superalloys, magnetic alloys, catalysts for the petroleum and chemical industries, and as a binder in tungsten carbide cutting tool materials. While catalyst producers use chemical forms of cobalt, superalloy and tungsten carbide makers use pure metal in cathode and extra-fine powder forms, respectively. Magnetic alloy production uses powder metallurgy techniques, and fabricators purchase either cathodes or powder forms.

Cobalt is produced from a variety of ores, and the processing, tailored for each deposit, depends on the type of ore in which the cobalt occurs, as figure 5-4 shows. Processes can be grouped into two general categories, pyrometallurgical and hydrometallurgical. The pyrometallurgical process is usually conducted in three stages. First, the minerals in the ore are concentrated. Second, a smelting or roasting process is used to produce a matte containing cobalt, with associated sulfur and the nickel and/or copper of the original ores. In the third step, the matte is treated chemically or electrolytically to separate the cobalt as metallic powder or cathodes, or as cobalt chemicals. In hydrometallurgical processes, the concentrated ore can be chemically processed without the intermediate smelting step but does require the application of heat and pressure.

Much of the cobalt content of mined ores is never recovered, owing to processing technologies and economics or to excessively low cobalt grades. Processes are such that a high recovery of the primary metal is often detrimental to the recovery of cobalt. In Zaire, for instance, the recovery of the cobalt content in the mined ores is only 30 percent, and in Zambia, 25 percent. (Cobalt is lost into tailings when the ores are initially concentrated and again when the concentrates are processed.) Yields of cobalt could be increased somewhat

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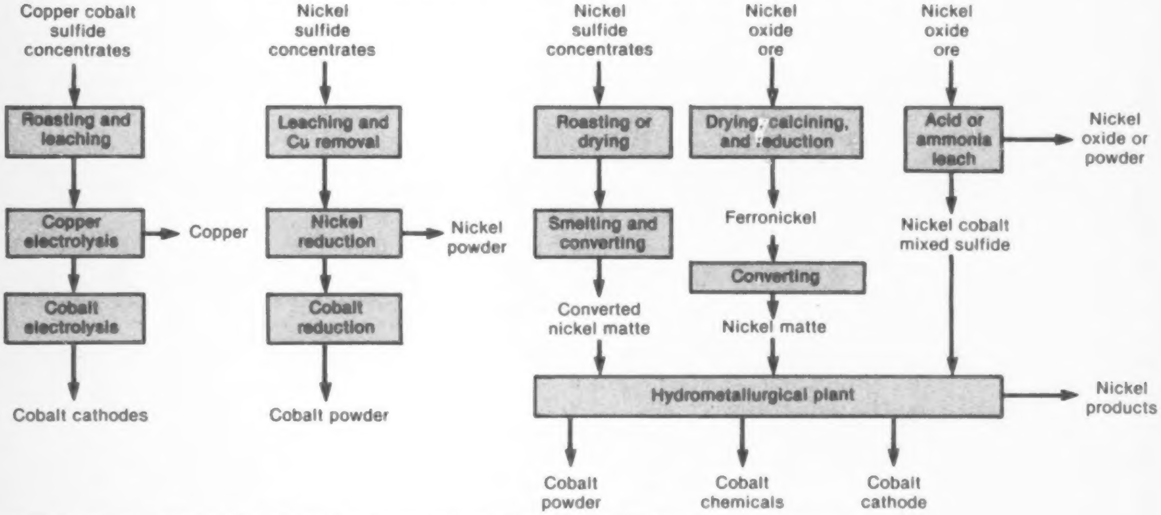
[78] U.S. Department of the Interior, Bureau of Mines, *Research 83*, p. 89.

[79] U.S. Department of the Interior, Bureau of Mines, *Mineral Industry Survey:* "Cobalt in February 1984."

[80] *Research 83*, op. cit., p. 91.

[81] National Materials Advisory Board, *A Review of the Minerals and Materials Research Programs of the Bureau of Mines*, p. 53; *Research 83*, op. cit., p. 83.

Figure 5-4.—Simplified Flowchart for the Production of Cobalt


Copper cobalt sulfide concentrates
Roasting and leaching
Copper electrolysis
Copper
Cobalt electrolysis
Cobalt cathodes
Nickel sulfide concentrates
Leaching and Cu removal
Nickel reduction
Nickel powder
Cobalt reduction
Cobalt powder
Nickel sulfide concentrates
Roasting or drying
Smelting and converting
Converted nickel matte
Nickel oxide ore
Drying, calcining, and reduction
Ferronickel
Converting
Nickel matte
Nickel oxide ore
Acid or ammonia leach
Nickel oxide or powder
Nickel cobalt mixed sulfide
Hydrometallurgical plant
Nickel products
Cobalt powder
Cobalt chemicals
Cobalt cathode

SOURCE: Charles River Associates, January 1984, *Processing Capacity for Critical Materials*, contract report for OTA.

by improving the efficiency of producing cobalt from the concentrates.

Nickel laterite ores tend to have cobalt associated with them in very low (0.02 to 0.11 percent) grades. These ores can be leached to separate out both nickel and cobalt. The economics of nickel production, if energy sources are available and competitively priced, usually demand, however, that the nickel ores be smelted into ferronickel. The cobalt contained in the smelted ores is either lost into the ferronickel or the slag. New Caledonia, for instance, produces limited amounts of cobalt from nickel laterite deposits, because its main effort is concentrated on producing ferronickel. The cobalt that is produced is a byproduct of some ore diverted into nickel metal production. Substantially higher amounts of cobalt are produced by one nickel mining firm in Australia as a result of its ore-matte-nickel metal processing steps. Other copper and nickel producers totally neglect the cobalt units in their deposits. In this category are the Hanna Mining operation at Cerro Matosa in Colombia, the Larco operations in Greece, Bonao in the Dominican Republic (Falconbridge), and the now-mothballed Inco operation in Guatemala.

Ferronickel was originally developed by New Caledonia's SLN and is used in lieu of nickel metal in the steel industry for the production of iron-nickel steels. Use of nickel metal is less energy-intensive than ferronickel, but ferronickel is not so much more expensive that steelmakers will alter their traditional methods. Nickel metal, however, must be used when the cobalt in ferronickel would be detrimental to the final product.

Domestic Processing Capacity

The United States has the operating capacity only to refine imported cathodes and process nickel-cobalt mattes or recycled materials into cobalt powder (table 5-23). In 1980, only one-tenth of the 10,825,000 pounds of cobalt metal consumed in the United States was produced domestically. The United States has no capacity to produce superalloy-grade cobalt. This material is all imported.

At its refinery in Louisiana, Amax Nickel produces cobalt powder, which is sold for applications other than superalloys. The plant, which mainly produces nickel, was originally designed with a 5 million to 6 million pound

Table 5-23.—U.S. Cobalt Processing Capacity

Product	Source material	Firm	Annual operating capacity
Superalloy grade			none
Powder	Imported smelted ores (matte)	Amax Nickel	1 million pounds Capable of production expansion to about 3 million pounds; can add electrolytic circuit to produce superalloy grade
Extra-fine powder	Cathodes (Zaire)	Carolmet	2 million pounds
	Domestic scrap	GTE	32,000 pounds (pilot plant operation)
Salts (chemical)	Recycled catalysts and scrap	Hall Chemical	1 million pounds Plus 3 million to 4 million pounds from projected plant; could add circuit to produce superalloy grade

SOURCE: Office of Technology Assessment.

U.S. Cobalt Consumption, 1982

End use	Thousand pounds contained cobalt
Superalloys	3,319
Steel alloys	326
Other alloys	2,829
Chemical	2,846
Other	148
Total	9,468

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982*.

annual output capacity for cobalt. Available feed and markets, however, have restricted the plant to a maximum of just over 1 million pounds. Estimates are that output could be raised to some 3 million pounds in a very short time, provided feed was available. In addition, all plans and design work have been completed for adding an electrowinning operation that would produce cobalt cathodes suitable for superalloy use. This plant modification would take approximately 2 years to complete. Feed for the plant is currently imported from Botswana and Australia in the form of mixed metal mattes. Other sources—e.g., Morocco, Uganda, and Peru—have been investigated and, while deemed technically possible, have been discarded as economically unfeasible. Amax's operation is a likely candidate to process and refine any domestic nickel-cobalt ores that might one day be produced.

At Carolmet, Inc., in North Carolina, an extra-fine powder for use in tungsten carbides is produced from cobalt cathodes imported from Zaire. The plant capacity is 1,000 tonnes (about 2 million pounds) annually. The other domestic source of extra-fine powder is the GTE Chemical and Metallurgical Division at Towanda, PA. Employing their own process, tungsten carbide scrap is used as the feed material, and a pilot plant now in operation has a capacity of 175 tonnes (32,000 pounds) annually. This process could also be used to purify substandard grades of cobalt and, if equipment were added to compact the powder produced, could possibly provide a source of cobalt for superalloy use.

Hall Chemical has plants in Ohio and Alabama to recycle catalysts and scrap metals, including cobalt, into chemical products for reuse. (See a discussion about the prospects for cobalt recycling in chapter 6.) A new plant has been planned by Hall that would more than triple its capacity, but the project has been halted by the recent recession. A large portion of this new capacity could be used exclusively for cobalt refining (from ore concentrates) with a lead time of 3 to 4 months. Installation of an electrolytic circuit to produce cobalt cathodes suitable for superalloys would require about 18 months.

Unlike the decline in domestic capacity for processing manganese and chromium, U.S. cobalt processing capacity has increased in the past 5 years with the addition of the two extrafine powder production facilities mentioned above. Still, operational domestic capability remains at the last stages of processing only. Initiation of domestic ore production would require the development of smelting and refining facilities, as well. This could be accomplished by upgrading the standing plants in order for the United States to have the greatest flexibility and ability to use the cobalt produced in the most critical applications (e.g., superalloys).

Manganese Production and Processing

The bulk of the world's manganese ore is produced in a few countries where large, discrete deposits of high-grade ore are mined by multinational firms. These deposits offer the possibility for expansion on a large scale, but substantial mine expansion would have to be accompanied by expansion of processing and transportation facilities. The Western Hemisphere has two sources of manganese ores, Mexico and Brazil. One new deposit may come onto the world market soon—part of the Grande Carajas project in Brazil. How much this operation will provide in terms of net gain in the world's export supply of manganese is unknown owing to Brazil's growing domestic steel industry.

The largest occurrences of worldwide economic manganese deposits are sedimentary in origin, formed from either volcanic or weathering activity. Residual ores, which make up a small part of the economic base, are formed in a concentration process similar to that for laterite deposits. Manganese is also found in hypogene deposits and with metamorphic rocks, primary sedimentary ores that have been subjected to changes in mineralogy and texture due to pressure and/or heat. Manganese is mined as an oxide and/or carbonate mineral, and both minerals are often present to varying degrees in each deposit.

The bulk of the ore mined today, however, is an oxide mineral. Initial processing of these ores involves only sorting by size and concentrating to increase the manganese content of the ores to 40 and 48 percent. (U.S. industry standard is 48 percent for ferroalloy production). Manganese carbonate minerals, on the other hand, must be converted to an oxide by roasting. Currently, only Mexico mines carbonate minerals, but this mineral type may eventually become a more important source as the higher grades of oxide ores are exhausted.

Manganese ores are classified as metallurgical, chemical, or battery grades. For metallurgical grade,[82] the iron, silica and especially phosphorus content are important. In battery grades the manganese content is expressed in terms of manganese dioxide, and these ores typically contain from 70 to 85 percent MnO_2 (44 to 53 percent manganese).

The United States imports 99 percent of its consumption of manganese ore and metal. In 1980, manganese ore accounted for 41 percent of U.S. imports of manganese, but an ongoing trend in producer countries to integrate ferroalloy production with ore mining is decreasing the ratio of manganese ore to ferroalloys in U.S. imports and throughout world markets.

In 1982, manganese ore was produced in 26 countries. Of these, 8 accounted for 98 percent of total world production. As indicated in table 5-24, the Soviet Union and South Africa produced 64 percent, while five countries (Gabon, Australia, Brazil, India, and China) each made a substantial contribution of over a million

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[82] About 90 percent of the world's manganese ores are destined for metallurgical uses.

Table 5-24.—World Manganese Ore Reserves and Production by Country (thousand tons)

Country producer	Reserves (recoverable metal content)	Production 1982 ore output	Estimated manganese content	Percent of world production
Australia	51,600	1,248	37-53	5
Brazil	20,900	1,433	38-50	6
China	15,000	1,760	20+	7
Gabon	110,000	1,667	50-53	7
India	21,500	1,596	10-54	6
Mexico	3,500	561	27+	2
South Africa	407,000	5,750	30-48	23
Soviet Union	365,000	10,140	30-33	41
Other	5,500	599		2
Total	1,000,000	24,754		100

SOURCE: U.S. Department of the Interior, Bureau of Mines
Reserves—*Mineral Commodity Profile 1983: Manganese*, p. 8, table 3.
Production—*Minerals Yearbook 1982*, vol. 1, table 9, p. 587.

short tons of ore. Mexico is the smallest producer of the eight at half a million short tons. Major exporters to market economy countries are South Africa, Gabon, India, Brazil, and Australia. India's exports are controlled by a government quota system and are destined primarily for Japan; the other four nations are the principal suppliers to the United States, Japan, and Western Europe.

Foreign Production of Manganese

In general, the manganese mining interests of each producer country are controlled by one or two firms, reflecting the concentrated nature of the deposits in these countries. Two private firms with primarily local, but also international, investors dominate South African production. Their deposits in South Africa occur in its northern Capetown Province in the Postmasburg and Kuruman (Kalahari) districts. The latter provides 75 percent of the total output.

The Soviet Union's government-controlled operations produce mainly from two areas in western Russia: the Nikopol Basin deposits, which contribute high-volume production; and those in the Tchiatura Basin, which provide the highest grade ores. Mexico and Gabon each have one privately operated firm in which the government holds a minority interest. Brazil's producing firms are a mixture of private and public sector interests. Brazil's manganese deposits in the Grande Carajas Development Project are being developed along with iron ore mines by Cia. Vale do Rio Doce (CVRD), a corporation jointly owned by the Brazilian government and local, private shareholders.

By contrast, manganese production in India and China is supplied by numerous small- or medium-sized operations scattered throughout each country. China's production is run by the national government, while India's ores are mined by a mixture of local private and state or national government firms.

U.S. firms participate in a number of foreign manganese mining operations (table 5-25). United States Steel has interests in Gabon's Comilog and South Africa's Associated Manganese; International Minerals & Chemical of New York has a minority interest in South Africa's Samancor. Bethlehem Steel owns part of Brazil's ICOMI and until the late 1970s was a partner in Mexico's Autlan. British investors are heavily involved with South African producers through traditional ties with the Anglo-American Corp., Ltd., Anglo Transvaal-Consolidated Co. Ltd., and General Mining Union Corp. Ltd (Gencor). These investment houses, or groups, hold interests in Samancor and Associated Manganese.

Historically, ores have been exported from producer countries after relatively minor beneficiation. The ore is ultimately moved to consumers by sea, which, along with transportation from a mining area to a shipping port, can account for a major portion of the cost of the product to consumers. Approximately two-

Table 5-25.—Manganese Mining Industry by Country

Country	Major firms	Ownership		
		Sector	Major holders[a]	Primary national identity
Australia	Groote Eylandt Mining Co.	Private	Broken Hill Prop. (100)	Local
Brazil	Industria e Comercio de Minerios S.A. (ICOMI)	Private	Bethlehem Steel (49)	U.S.
		Private	CAEMI (51)	Local
	Urucum Mineracao S.A.	Private/ government	CVRD[b] (47)	Local
		Various	Local	
Gabon	Compagnie Minere de l'Ogooue S.A. (Comilog)	Government	BRGM (19)	French
		Government	(15)	Local
		Private	Imetal (16)	French
		Private	U.S. Steel (41)	U.S.
Mexico	Cia. Minera Autlan S.A. de C.V.	Government	(34)	Local
		Private	Various	Local
South Africa[c]	SA Manganese Amcor Ltd. of S.A. (Samancor)	Private/ government	African Metals[d] (40)	Local
		Private	AngloAmer (32)	Local/U.K.
		Private	Gencor (7)	Local
		Private	Lavino[e] (10)	U.S.
	Associated Manganese Mines of S.A.	Private	Assoc Ore & Metal[f] (38)	Local
		-	U.S. Steel (20)	U.S.
			Fox Street (34)	U.K.

[a] With approximate percentage of control, if available.
[b] Cia. Vale do Rio Doce, which also controls the emerging production at Carajas in Brazil.
[c] There are six finance houses (the "Groups") which dominate the South African industry: The Anglo American Corp. of S.A. Ltd. (AngloAmer); Gold Fields of S.A. Ltd.; General Mining Union Corp. Ltd. (Gencor); Rand Mines/Barlow Rand; Johannesburg Consolidated Investment Co. Ltd. (JCI); and Anglo-Transvaal Consolidated Investment Co. Ltd. (AngloTC).
[d] Owned by Iscor, a state-owned integrated steel firm, (49.75%) and Gencor (50.25%).
[e] Wholly owned by International Minerals and Chemical (U.S.).
[f] Owned by AngloTC and AngloAmer.

SOURCES: E&MJ *1983 International Directory of Mining;* Bureau of Mines, *Mineral Commodity Profile 1983: Manganese*; Office of Technology Assessment.

thirds of the manganese ores traded on the free market are sold by contracts (generally of 1 year's duration) between producer and industrial user. Other forms of trade include captive sales within integrated firms (e.g., between Gabon and U.S. Steel) and spot market purchases when excess supplies are available.

World trade in manganese is now undergoing a shift from basic ores to the higher processed manganese ferroalloys. This new ferroalloy production capacity competes primarily with plants close to steelmaking centers in the United States, Western Europe, and Japan. As table 5-26 shows, however, not only the ore-producing countries have increased production of ferroalloys. Some other countries have increased or added local production to meet the domestic and export markets steel industry demand. While the major manganese ferroalloy producing countries in 1980 were the Soviet Union (23 percent of world's total), Japan (14 percent), South Africa (9 percent), and France (8 percent), the exporting countries were principally South Africa, France, and Norway. More recently, Brazil has increased its exports because its ferromanganese production capacity is far in excess of its domestic steel demand. South Africa remains the world's leading supplier of manganese ferroalloys, and Western Europe and the United States are the major importers. In 1982 the United States received 50 percent of its manganese ferroalloys from South Africa and 21 percent from France.

All of the major ore producers, with the exception of Comilog in Gabon, have the capability to produce manganese ferroalloys. Trade in manganese ferroalloys may not be replacing trade in ores as rapidly as ferrochromium is replacing chromite. Gabon is at the discussion stage regarding ferroalloy production, but any actual projects will depend on development of an energy source. Australia is restrained from increasing its ferroalloy capability by the lack of low-cost energy. Only in

Table 5-26.—Ferromanganese and Silicomanganese Production by Country
(thousand short tonnes, gross weight)

Country[a]	1974	Percent of total	1980	Percent of total	Percent change 1974-80
Argentina	34	0.5	39	0.5	15
AUSTRALIA	69	1.1	124	1.7	80
Belgium	108	1.7	94	1.3	−13
BRAZIL	124	2.0	303	4.0	144
Canada	100	1.6	95	1.3	−5
CHILE	12	0.2	6	0.1	−50
CHINA	NA		390	5.2	
France	587	9.4	551	7.3	−6
Great Britain	91	1.5	57	0.8	−37
INDIA	163	2.6	193	2.6	18
ITALY	133	2.1	141	1.9	6
JAPAN	1,182	19.0	969	12.9	−18
North Korea	0		77	1.0	
SOUTH KOREA	0		60	0.8	
MEXICO	70	1.1	172	2.3	146
Norway	577	9.3	496	6.6	−14
Peru	0		1	0.0	
Poland	138	2.2	183	2.4	33
SOUTH AFRICA	400	6.4	650	8.6	63
Spain	211	3.4	239	3.2	13
SOVIET UNION	1,075	17.3	1,644	21.8	53
United States	740	11.9	377	5.0	−49
Venezuela	0		4	0.1	
West Germany	353	5.7	248	3.3	−30
YUGOSLAVIA	44	0.7	73	1.0	66
Zimbabwe	0		3	0.0	
Other[c]	13	0.2	334	4.4	2,469
Total	6,224	100.0	7,523	100.0	16

[a] Upper case indicates country was ore producer in both years, but did not necessarily cover its needs.
[b] Produced ore in 1974 only.
[c] In 1974 includes Thailand and Sweden; In 1980 includes BULGARIA, Czechoslovakia, East Germany, and Portugal. All were ferroalloy producers in 1974 but amount of manganese ferroalloys unknown; thus, total shown for 1974 production is not accurate.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook*, 1976 and 1981.

Tasmania, south of the Australian mainland, where hydropower is available, is it economic to produce ferroalloys. However, ore must be shipped approximately 3,000 miles from the north coast of Australia by sea, reducing some of the cost advantage of integrated ore and ferroalloy production. New manganese ferroalloy production is being added in Brazil and India. During recessionary periods this production appears on the export market instead of being consumed in domestic steel industries.

As indicated by table 5-27, there have been shifts over the last 20 years in the relative output of ore producer countries. Most notably, world production has been increasingly concentrated in the eight producer countries listed. From 79 percent in 1960, they now supply 97 percent of the world's total ore needs. The most recent producer to enter the world market was Australia's Groote Eylandt in 1966. There is one new manganese mining project now under development; Carajas in Brazil may add export production by 1986.

Between now and 2000, virtually all of the growth in total world output of manganese ore will come from the expansion of existing mines rather than the opening of new mines. A decrease or cessation of production from one source would force expansion of production from the remaining suppliers. Current world mining capacity is substantially greater than demand, as shown in table 5-28. In 1981 only 73 percent of existing capacity was used. That unused capacity was 1½ times South Africa's total output. Under such conditions, rapid expansion of production from existing mines is quite feasible. In times of tighter markets, there is potential for expansion of current mine ca-

Table 5-27.—Historical Manganese Ore Production, 1960-80, by Country
(thousand short tons, gross weight)[a]
(percent of world total)

	1960		1965		1970		1975		1980	
Producer country	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
Australia	68	<1	112	1	828	4	1,714	6	2,226	8
Brazil	1,101	7	1,539	8	2,071	10	2,376	9	2,515	9
China	1,323	9	1,102	6	1,100	5	1,100	4	1,750	6
Gabon	0	0	1,411	7	1,602	8	2,444	9	2,366	8
India	1,321	9	1,815	9	1,820	9	1,688	6	1,814	6
Mexico	171	1	144	1	302	2	473	2	493	2
South Africa	1,316	9	1,738	9	2,954	15	6,359	23	6,278	22
Soviet Union	6,473	43	8,351	43	7,541	38	9,324	34	10,750	37
Subtotal	11,773	79	16,212	83	18,218	91	25,478	94	28,192	97
Other	3,216	21	3,345	17	1,866	9	1,598	6	869	3
Total	14,989	100	19,557	100	20,084	100	27,076	100	29,061	100

[a] Ores vary widely in contained manganese; see table 22.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbooks*, 1961, 1966, 1971, and 1981.

Table 5-28.—Manganese Mine Capacity and Usage in 1981, by Country
(thousand short tons, contained manganese)

Producer country	Estimated annual capacity	Percent in use	Estimated unused capacity
Australia	1,300	58%	550
Brazil	1,350	76	320
China	550	96	22
Gabon	1,300	64	470
India	800	72	225
Mexico	300	81	60
South Africa	3,000	72	840
Soviet Union	3,800	80	760
Other	485	63	178
Total	12,885	73	3,610

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Commodity Profile 1983: Manganese.*

pacity, especially in South Africa, Gabon, and Australia. Given a year or more extra lead time, Brazil and Mexico could increase their production, as well.

Carajas in Brazil and a site at Tambao in Upper Volta are the only deposits of manganese ore that might alter future supply patterns. The Tambao deposit suffers from its location, far from existing transportation facilities. Activity there was halted at the end of the exploration phase. Although the Carajas project is proceeding, obtaining capital for development of such deposits is difficult because they must produce ore for markets that are already filled by suppliers with large reserves. Thus, the current ore producer countries will be the major producers of the future. Among these, the major exporters are expected to be South Africa, Gabon, and Australia, all of which have substantial resources in relationship to their own domestic needs.

In contrast, India's ore production is increasingly tied to its expanding domestic steel production. India is also limited in the export market by the low grade of its manganese deposits and the inefficiency of its overall operations. Brazil's future as a major supplier to the export market is uncertain. Facing the depletion of its most productive deposit in the 1990s, Brazil has instituted a policy of reserving much of its ore, including 50 percent of Carajas' future production, for ferroalloy production and the domestic steel industry. If the Carajas deposit reaches its planned output of 1 million tons of ore per year and is the sole source of exports, this policy will result in an export level of about 50 percent less than current exports from Brazilian manganese mines.

The Soviet Union was once a major supplier of manganese ore to world markets, but since the 1970s, it has concentrated on trade within the Eastern bloc. Historically, this provided for self-sufficiency among this group. In the 1980s, however, some Eastern bloc countries (e.g., Romania, Czechoslovakia, and Poland) have begun satisfying a portion of their ore needs by importing from the same sources as the market economy countries. The Soviet Union negotiated with Gabon for supplies of ore in 1984 and has purchased from Gabon, India, and Australia in the recent past. The assumption in the West is that, since the ore production tonnages being reported from the Soviet Union are not declining, they are experiencing a depletion of higher grade material. China produces for internal consumption, and this policy is expected to continue as the country's domestic needs increase.

Following is a brief description of the operations of the producer countries of interest, with discussion of major factors that may affect future development and production of ore and ferroalloys.

Australia

Groote Eylandt Mining Co., a wholly owned subsidiary of the Broken Hill Proprietary Co. (BHP)—Australia's sole integrated steelmaker—produces from open pit mines located on an island 50 kilometers off the coast of the Northern Territory. Beneficiated ore is hauled 16 kilometers to Milner Bay for ocean shipping. Capacity has recently been increased to 2.6 million tons per year with the installation of a plant to upgrade ore fines (which were previously discarded). Further expansion plans to increase capacity to 3 million tons per year have been delayed because of unfavorable market conditions.

Barriers to expansion are the concentration plants and loading facilities at Milner Bay. Company officials have stated that, given an emergency, significant expansion in these areas would take an estimated 3 years to complete. With government financial assistance and guarantees of long-term markets, facilities could be in place in 2 years. Australia is currently heavily reliant on Japan as an export customer because of high shipping costs to other major consumers. Its one manganese ferroalloy plant is located in Tasmania and was originally constructed to supply BHP steelmaking needs. Recent expansion, however, has been based on the export market.

Brazil

There are two principal ore-producing areas in Brazil, one in the Federal Territory of Amapa and the other in the Matto Grosso state. The existing mines' location, remaining life, or ore quality limit their attractiveness. The Amapa deposits, owned by ICOMI, are located in northern Brazil, produce half of Brazil's output, and are operated mainly for exports because of the high cost of transporting the ores to the steelmaking center in southern Brazil. The steel plants are supported by the Matto Grosso operations of Urucum Mineraco S.A., and a small operation in Minas Gerais. ICOMI's reserves are expected to be depleted by the 1990s. Production by Urucum (about 100,000 tons of manganese ore in 1980) is hampered by the quality (high alkali content) of the ores and accessibility of the deposits, which lie 2,000 kilometers from the nearest port. Future increases in production at Urucum could come from an underground deposit if manganese prices were to double.

The Grande Carajas Development Project, some 900 kilometers from the Atlantic coast in the state of Para, is a mineral development that includes iron ore, manganese, copper, nickel, gold, tin, and bauxite. The project is financed by national and international loans. Participants have included the EEC, Japan, West Germany, and the World Bank.

Three manganese deposits have been identified: Azul, Buritirama, and Serenc. Development of the Azul deposits (with reportedly 16 million to 24 million tons of manganese)[83] is the second phase of the project. The initial phase has included the preparation of iron ore mines, along with the construction of the necessary infrastructure. A railroad to Sao Luiz on the coast and new ocean port facilities at Ponta da Madeira are expected to be completed in 1986, when manganese production of metallurgical grade ores will begin.

The deposit is currently being exploited for battery-grade ores which, because of their high value (grades up to 75 percent MnO_2), can be economically transported by truck to the coast for shipment. The metallurgical ores will be hauled from an open pit mine 20 kilometers to the railhead at the iron ore mine area. Processing will consist of washing and crushing, using existing facilities originally constructed as a pilot plant for the iron ores. It is expected that the output from the manganese mine will eventually total 1 million tonnes (900,000 tons) of about 48 percent manganese ores per year. With additional beneficiation equipment, the deposit could support up to 2 million tonnes per year.[84] This extension of facilities, however, must await favorable market conditions. An onsite ferroalloy plant was included in the original concept but lack of financing has shelved these plans.

U.S. Steel was involved in the discovery of the Carajas deposit, but its interest was bought out by CVRD in 1976. Utah International (previously owned by General Electric but in April 1984 transferred to Broken Hill Proprietary of Australia) holds the rights to the development of the Buritirama manganese deposits at Carajas; however, there are no development plans being considered for the near future.[85] The Sereno deposits are currently unexploited. Together, these deposits have considerably less identified reserves and resources than does Azul.

Brazil has five firms involved in producing various types of manganese ferroalloys for both domestic and export purposes.

Gabon

Market conditions now hold output from Gabon's Moanda mines well below the 1979 peak of 2.5 million tons. These mines are capable of supporting up to 4 million tons per year but shipments are limited to 3 million tons per year via the available transportation system.[86] This involves the use of a 76-kilometer aerial ropeway connection to the Congo's rail system, followed by a 560-kilometer rail trip to the port of Pointe Noire. An alternate route, the Trans-Gabon railway, has been under construction since 1974. Completion to the mine site near Franceville (500 more km) plus upgrading of the timber port at Owendo, Gabon, would make possible the shipping of the maximum of 4 million tons per year from Moanda, although current market conditions would not make increased shipments economically feasible. Development of ferromanganese facilities are under discussion, but no firm plans have yet been made.

Mexico

The Molango district deposits in Mexico are mined by the Cia. Minera Autlan S.A. de C.V. and represent significant reserves and resources which could support a substantial increase in production if the market and investment funds were available.[87] The deposits consist of two types, carbonates and oxides. The carbonate ores represent the bulk of the minerals present, and Autlan has reported measured reserves of 28.4 million tons of carbonate ore at 27.5 percent manganese (from a total estimated resource of 1.5 billion tons at 25 percent).

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[83] Louis Fuchs of the CVRD office in New York, personal communication, December 1983. Total reserves were placed at 65 million tonnes of ore at about 48 percent manganese. Of this amount, 10 million tonnes consists of battery grade material at 74 to 75 percent MnO_2. The National Materials Advisory Board, in *Manganese Reserves and Resources of the World and Their Industrial Implications*, 1981, reported a crude ore resource of 65 million tonnes that would wash 44 million tonnes of product grading 46.5 percent manganese. Thomas Jones, commodity specialist at the Bureau of Mines, reports 45 million tonnes of ore at 40 percent manganese.

[84] Louis Fuchs, op. cit.

[85] Jean Goity, Public Relations, Utah International, San Francisco, personal communicaton, February 1984.

[86] Robert L'esperance, U.S. Steel Corp., Pittsburgh, PA, personal communication, August 1983.

[87] NMAB 81, p. 39.

After mining and beneficiation, these carbonate ores are converted to nodules of manganese oxide (39 to 40 percent manganese) in a rotary kiln near the mines. One of the difficulties that Autlan manages to overcome is the rugged terrain of the Sierra Madre Oriental in which their mines (open pit and underground) are located. In these precipitous and densely vegetated mountains, elevations vary from 200 to 2,600 meters above sea level. The export ores (50 percent of Autlan's production) must be hauled 260 kilometers to Autlan's maritime terminal at Tampico on the Gulf Coast for shipment.

The quality of Autlan's ores has been questioned because of their high silica content and relatively low grades. The general commercial standard for ores used in ferroalloy production is 48 percent manganese. Although Autlan produces ferromanganese with its 40 percent ores, its customers blend the ores with higher grade ores in order to produce 78 percent ferromanganese, the U.S. industry standard for a high-carbon product. The high silica content makes the ores most suitable for the production of silicomanganese.

Several projects are currently being studied by Autlan to enable them to expand their production. Among them are the opening of a new open pit mine at Noapa, the installation of a second rotary kiln, and a new water supply system. Physically, the resources could support a doubling of production, but manganese prices and demand in the 1980s will not support such a change in policy. The Trade and Development Program in the U.S. International Development Cooperation Agency has been active in studying the manganese deposits in Mexico and in attempting to interest U.S. investors in joint ventures with Autlan to expand its production.[88]

South Africa

Associated Manganese and Samancor each own mines in both the Postmasburg and Kuruman (Kalahari) districts. The capacity of these mines has been estimated to be greater than 9 million tons of ore per year. Even at current operating rates, the reserves are sufficient to last hundreds of years, and South African production is capable of rapid expansion. Transportation, however, could be a limiting factor because ores must be shipped south from both mining districts by rail to either Port Elizabeth (950 km directly south) or to Saldanha Bay, north of Capetown (800 km southwest).

South Africa has four firms engaged in producing various manganese ferroalloys, plus two producing manganese metal. Ferroalloy production is integrated within mine producing firms, either directly or through "group" investment houses.

Potential Source

At Tambao, Upper Volta, a remote area 350 kilometers from a railhead, some 13 million tonnes (12 million tons) of 52 percent oxide ores have been identified. Extensive exploration work was done and feasibility studies were completed during the late 1970s while the project was being considered by a consortium consisting of a number of international firms including Union Carbide. The group subsequently fell apart owing to the divergent goals and conflicting interests of its members.[89] It would take about 5 years to bring the area into production and provide the infrastructure needed to export the ores (the construction of a railroad and a port). Since Upper Volta is a landlocked country, arrangements would have to be made with the Ivory Coast for rail transiting and the development of port facilities.

Domestic Production of Manganese

Domestic manganese has made some contributions to U.S. needs, especially in wartime. During the latter part of the 19th century, the United States produced sufficient manganese from domestic deposits to meet its needs. With the growth of the U.S. steel industry since 1900, however, domestic manganese production has not been able to keep up with demand. Despite a variety of government incentive programs, domestic production was only 23 percent of consumption during World War I, 13 percent during World War II, and 8 percent during the Korean war. In 1944, manganese ores were produced in more than 20 States, but Montana, Nevada, New Mexico, Arizona, and Arkansas have provided the bulk of the historical production.

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[88] See U.S. International Development Cooperation Agency, Trade and Development Program, *The Molango Area (Mexico) Manganese Deposits of Compania Minera Autlan—The Largest Known Manganese Ore Reserve in North America*, June 1983.

[89] Benjamin Brittain, Union Carbide Corp., personal communication, August 1983.

Today, aside from minor amounts, the prospects for production of manganese from U.S. deposits is highly unlikely except during a sustained cutoff of imported ores. And, unless world prices rose considerably during such a period, Federal Government production incentives would be required.

There has been no *manganese ore* (table 5-29) produced in the United States since 1970.[90] The last year of production of *ferruginous manganese* ores was 1981 and totaled 22,165 tons of contained manganese from Cuyuna North Range in Minnesota (20,712 tons) and from New Mexico (1,453 tons). The only domestic production in 1984 is of *maganiferous iron ores* from South Carolina which are used in pigments (total production in 1982 of this ore type contained 1,325 tons of manganese). Iron ores consumed in the United States in 1982 provided approximately one-third of the manganese used in domestic steelmaking. Since 30 percent of those iron ores were imported (mainly from Canada), domestic sources can be credited with 23 percent of that input.[91]

Table 5-29.—Definition of Manganese-Bearing Ores

Type	Description
Manganese ore	Ores containing more than 35 percent Mn
Ferruginous manganese ore	Ores containing from 10 to 35 percent Mn
Manganiferous iron ore ...	Ores containing from 5 to 10 percent Mn

SOURCE: *Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese As An Alloying Element in Steels*, OTA contract report, 1983.

Eight U.S. deposits of manganese were considered in a Bureau of Mines Minerals Availability System Appraisal[92] in 1982 and were termed "submarginally subeconomic." The report concluded that incentive prices ranging from $8 to almost $35 per long ton unit[93] of contained manganese would be required in order to encourage production from these deposits, as compared with the market value at that time of $1.70 per long ton unit.[94] Annual production from these sources would peak at 900,000 tonnes (818,000 tons) of recoverable manganese 6 years after simultaneous development began, declining thereafter (to 578,000 tons per year within 10 years, for instance) unless additional resources were located and/or technological improvements were made in mining or processing of the ores.[95] (U.S. apparent consumption of manganese was 1.25 million tons in 1979 and 672,000 tons in 1982.)

The more significant deposits among the identified domestic manganese resources are those of the Artillery Mountains, Arizona; Batesville, Arkansas; San Juan Mountains, Colorado; Aroostook County, Maine; and the Cuyuna Range in Montana. Collectively this group is estimated to contain over 70 million tons of manganese.[96] The average grade of manganese in U.S. deposits is generally less than 10 percent which compares unfavorably with the major world producers who extract manganese from deposits with grades of from 27 to 53 percent.

The National Materials Advisory Board in 1976 concluded that:

> The U.S. land-based manganese resources of significant size are very low in grade and should not be developed except in a dire emergency.[97]

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[90] Thomas Jones, Jr., U.S. Department of the Interior, Bureau of Mines, *Mineral Commodities Profiles 1983: Manganese*, p. 10.

[91] See the discussion on manganese and steelmaking in ch. 6.

[92] Catherine C. Kilgore and Paul R. Thomas, U.S. Department of the Interior, Bureau of Mines, *Manganese Availability—Domestic, A Minerals Availability System Appraisal*, Information Circular/1982 No. 8889.

[93] A long ton unit is 22.4 pounds of manganese and is the standard unit for quoting manganese ore prices.

[94] Another study has calculated a cost estimate for U.S. production at four times that of South African producers in 1980 dollars. See *Processing Capacity for Critical Materials*, op. cit.

[95] Kilgore, et al., op. cit., p. 1.

[96] U.S. Bureau of Mines, *Mineral Commodity Profile 1983: Manganese*, p. 7.

[97] National Materials Advisory Board, *Manganese Recovery Technology*, NMAB-323 (Washington, DC: National Academy of Sciences, 1976), p. 1.

The NMAB study stated that, while there were no known deposits in the United States of manganese ores that could be exploited at current or even substantially higher prices, the best suited deposits for development in an emergency on a significant scale were those of the Cuyuna Range and in Aroostoock County.[98] The Bureau of Mines' appraisal results concur. In its estimates of mining capacity, as summarized in table 5-30, these deposits could contribute the highest levels of production and be able to operate from 14 to 61 years.

In analyzing the impact of different variables (e.g., beneficiation and transportation costs, byproduct prices, State severance taxes), the Bureau of Mines determined that technologic improvements leading to a reduction in the cost of beneficiation methods would be the single most significant factor for improving the economic status of these deposits. Substantial increases in byproduct prices, for instance, would be necessary to significantly decrease the incentive price needed for domestic manganese. A 9-percent increase in iron ore prices would produce a 4-percent decrease in the manganese incentive price at Cuyuna Range, for instance. (Iron is also a byproduct of the Aroostoock area; silver at Hardsell in Arizona; and silver, lead, and zinc at Montana's Butte District.)[99]

Domestic Mining and Processing Technology Prospects

Manganese deposits in the United States are in a variety of environments ranging from rela-

Table 5-30. U.S. Manganese Resources and Potential Production

	Demonstrated resource			Estimated annual mine capacity		
Property name by State	Manganese grade (percent)	Ore (thousand tonnes)	Contained manganese (thousand tonnes)	Ore (thousand tonnes)	Contained manganese (thousand tonnes)	Estimated minelife (years)
Arizona:						
Hardshell Mine	15.0	5,896	804	536	73	11
Maggie Mine (Artillery Peak)	8.8	8,441	671	328	26	26
Colorado:						
Sunnyside Mine	10 0	24,909	2,264	635	58	39
Maine—Aroostook County:						
Maple Mtn/Hovey Mtn	8.9	260,000	20,965	4,263	344	61
North District	9.5	63,100	5,472	2,620	227	24
Minnesota:						
Cuyuna North Range (SW portion)	7.8	48,960	3,490	3,570	254	14
Montana:						
Butte District (Emma Mine)	18.0	1,232	202	400	65	3
Nevada:						
Three Kids Mine	13.2	7,230	868	1,050	126	7
Total		419,768	34,737	13,401	1,174	

SOURCES: Resources, ore grades, proposed ore mining capacity from U.S. Department of the Interior, Bureau of Mines, *Manganese Availability—Domestic*, IC8889/1982. Balance, calculated by OTA using that data.

Apparent U.S. Manganese Consumption

Tons	Contained metal
1979	1,250,000
1982	672,000

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries, 1984*, p. 96.

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[98] NMAB-323, p. 14 and p. 1.

[99] Kilgore, et al., op. cit., pp. 9-10.

tively soft deposits to steeply dipping veins in hard rock. Thus, standard mining methods would include both underground and open pit operations.

Solution mining of manganese ore has been proposed. Two variations are possible. In one the ore is mined, spread on the surface, and a solvent is applied. This "heap leaching" process produces a solution of manganese which can be collected. In another process, "in situ leaching," a hard-rock ore body is blasted to induce permeability and the solvent is pumped into the fractured ore body. The leached solution is then pumped out of the mine. These solution mining techniques for manganese[100] were under evaluation by the Bureau of Mines for 2 years but the project was eliminated from the fiscal year 1984 budget. Preliminary economic analysis indicated that leached manganese could compete favorably with foreign manganese ores for chemical (battery) industry markets but not for the ferromanganese industry.[101] Conventionally mined metallurgical ores bound for ferromanganese production require little processing after mining; solution mined ores are uncompetitive. Another conclusion of the study was that solution mining applied to domestic manganese-silver ore bodies would permit the separation of these minerals not possible by other techniques. The private sector has expressed some interest in the process in order to obtain the silver values. Manganese could be a byproduct of any such operation. A pilot plant is apparently in operation in the Artillery Peak area of Arizona, funded by major mining companies, to test a heap leaching process on manganese ores.

Most of the U.S. manganese resources are not amenable to normal beneficiation methods of gravity and flotation alone owing to their low grades. Chemical and roasting processes (e.g., the ammonium carbamate leach and sulfur dioxide roast processes) have been developed for beneficiating domestic manganese. These processes have so far proved to be too costly for extended use. Grinding and fine-particle concentration processes might improve the economics.[102] A study to identify the three most promising processes for recovering manganese from low-grade domestic sources was underway by the Bureau of Mines in 1984.

Domestic and Foreign Manganese Processing

Manganese is used as a processing and alloying agent of steel and an alloying agent in nonferrous materials. Although manganese is used to some extent in the mineral form in which it occurs in the ore, for the most part it is useful only after several processing steps convert it to a metal or metal alloy. Steelmaking requires manganese ferroalloys with high-, medium-, or low-carbon content, and silicomanganese. Aluminum alloys are made with additions of pure metallic manganese. The compositions of these materials are shown in table 5-31. Figure 5-5 is a simplified flowchart for the production of these alloys showing the close relationship that exists between the processes for the various forms of ferroalloys.

The U.S. steelmaking industry has a standard of 78 percent manganese content for high-carbon ferromanganese, and this product is traditionally made from 48 percent manganese ores. It is technically possible to produce steel from a lower grade ferromanganese, and internationally this standard is not as rigorously applied. This is a possible area wherein diversity of supply of manganese could be broadened by turning to lower grade deposits such as those in Mexico if the need should arise.

Manganese Ferroalloys[103]

The major manganese commodity is high-carbon ferromanganese, used in the production of steel. It is now commonly produced in sub-

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[100] See various Bureau of Mines papers including "Arizona's Artillery Peak Manganese Deposits and Their Potential for In Situ Leaching" (1981) by Peter G. Chamberlain; "Recovery of Silver From Manganese Ores" (1984) and "Recent Research on Leaching Manganese" (1983) by Peter G. Chamberlain, John E. Pahlman, and Charles A. Rhoades.

[101] U.S. Department of the Interior, Bureau of Mines, *Research 83*, op. cit., p. 5. Also National Materials Advisory Board, *A Review of the Minerals and Materials Research Programs of the Bureau of Mines*, op. cit., 1984.

[102] Silverman, et al., op. cit., p. 159.

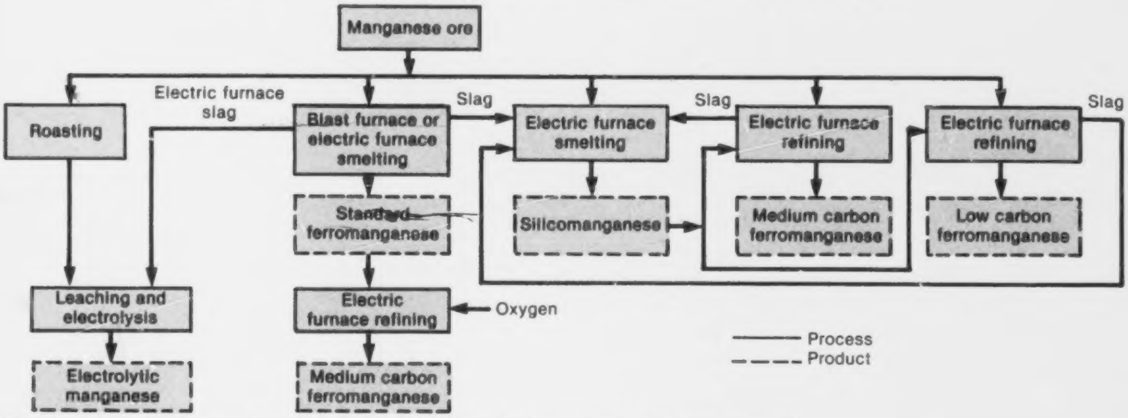
[103] This discussion of manganese ferroalloy processes is taken primarily from Charles River Associates, op. cit.

Table 5-31.—Composition of Manganese Alloys

	Manganese	Carbon	Silicon
Ferromanganese:			
High carbon	74-82	7.5	1.2
Medium carbon	80-85	1.5	1.2
Low carbon	80-90	0.7-0.75	1.2
Silicomanganese	65-68	1.5-3.0	12.5-21
Ferromanganese-silicon	63-66	.08	28-32
Manganese metal	99.5	.005	.001

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Commodity Profile 1983: Manganese.*

Figure 5-5.—Simplified Flowchart, Manganese Ore to Industry Use


Manganese ore
Roasting
Electric furnace slag
Blast furnace or electric furnace smelting
Slag
Electric furnace smelting
Slag
Electric furnace refining
Electric furnace refining
Slag
Standard ferromanganese
Silicomanganese
Medium carbon ferromanganese
Low carbon ferromanganese
Leaching and electrolysis
Electric furnace refining
Oxygen
Electrolytic manganese
Medium carbon ferromanganese
Process
Product

SOURCE: Charles River Associates, *Processing Capacity for Critical Materials,* OTA contract study, January 1984.

merged arc electric furnaces, similar to those used for ferrochromium, rather than the original blast furnace method. (See the previous chromium processing section for a general discussion on ferroalloy production in submerged arc furnaces, the degree of convertibility between ferrochromium and ferromanganese furnaces, and the applicability of new technology to ferroalloy production.)

In the United States the blast furnace has been entirely supplanted by the electric furnace for the production of ferromanganese. The last ferromanganese blast furnace was shut down in 1969 by Bethlehem Steel after being damaged by the Johnstown, PA, flood. Limited blast furnace capacity still exists in Western Europe and South Africa, but all new furnace capacity worldwide is of the electric type.

Pig iron blast furnaces can be considered as alternative capacity for ferromanganese production. As the ferromanganese blast furnaces were generally adapted from old pig-iron furnaces, they are smaller than current pig-iron furnaces, and the hot blast temperatures are lower (about 1,000° to 2,000° F) than for modern iron furnaces. The main disadvantage of using the blast furnace for the production of ferromanganese is that the coke requirement is almost twice that for the electric furnace, since coke must be used both as a reducing agent and to supply the thermal energy for the reaction. Both furnace types require a blend of manganese ores and dolomite or limestone as a fluxing agent. Existing small, pig-iron blast furnaces could readily be converted to produce ferromanganese at minimal capital cost. Operating costs would be higher than for electric furnaces.

Silicomanganese is produced in an electric furnace similar to that used for ferromanganese production. The manganese content in the slag from a standard ferromanganese furnace operation normally ranges from 30 to 40 percent and is used as feed for the production of silicomanganese. Efficient production requires that both standard ferromanganese and silicomanganese furnaces be located in the same plant.

The silicomanganese furnace has a smaller crucible with smaller electrode diameter and closer electrode spacing than does a standard ferromanganese furnace. If a furnace designed for ferromanganese production has the capacity in its environmental control (gas-cleaning) system, it can be operated at higher power levels (to compensate for the charge property difference) to produce silicomanganese.

Medium- and low-carbon ferromanganese is produced by refining various high-carbon ferromanganese products in open arc furnaces. These furnaces are different from submerged arc furnaces in that the electrodes are not suspended deep within the charge.

Manganese Metal

Metallic manganese is commonly produced by an electrolytic process from an acidic solution of manganese ore. South Africa, Japan, and the United States are manganese metal producers.

Processing Distribution and Capacity

The worldwide distribution of processing capacity for ferromanganese, silicomanganese, and manganese metal is shown in table 5-32. Although having dramatically declined in capacity in the last decade, the United States still has the capability to produce all types of manganese ferroalloys and electrolytic manganese metal. Table 5-33 shows the growth of imports over the last decade that have eroded the U.S. industry, ferroalloys having made the greatest inroads.

Of the six firms in the United States still credited with the capacity to produce manganese ferroalloys (out of 10 in 1979), three have shut down their plants, and the others are operating at very low rates. A contributing factor to this demise—other than import penetration—was the steel industry depression during the early 1980s. Elkem Metals plant at Marietta, OH, for instance, in early 1984 had only 3 furnaces of an original 14 in operation; by mid-

Table 5-32.—Manganese Ferroalloys and Metal Production Capacity—1979
(tonnes, gross weight)

	Ferromanganese				
Country	High carbon	Medium carbon	Low carbon	Silicomanganese	Manganese metal
Argentina	40,000			2,000	
Australia	135,000				
Belgium	150,000	30,000		50,000	
Brazil	117,000	61,000	600	61,600	
Canada	90,000			50,000	
Chile	5,000			1,000	
France	580,000	50,000		60,000	
West Germany	298,000	35,000			
India	229,000	3,000		13,000	
Italy	130,000	15,000	5,000	4,000	
Japan	700,800	205,820		535,200	6,000
Mexico	135,000				
Norway	370,000	50,000	5,000	220,000	
Peru	3,600				
Portugal	150,000				
South Africa	493,000	10,000		122,000	35,000
Spain	60,000	35,000	10,000	45,000	
Taiwan	4,200			3,000	
Great Britain	80,000		300		
United States	453,000	36,000		125,000	11,000+
Yugoslavia	40,000			5,000	
Total	4,263,900	530,820	20,900	1,296,800	52,000

SOURCE: Charles River Associates, *Processing Capacity for Critical Materials*, OTA contract report, January 1984.

Table 5-33.—Managanese Ferroalloys and Metal: U.S. Imports and Consumption
(gross weight, short tons)

	Ferroalloys	Metal
1970:		
Imports	290,946	NA
Consumption	1,000,611	NA
Imports as percent of consumption	29	—
1974:		
Imports[a]	421,222	2,506
Consumption	1,115,395	34,748
Imports as percent of consumption	38	7
1980:		
Imports[b]	605,703	7,508
Consumption	789,076	25,092
Imports as percent of consumption	77	30

[a] Metal imports include unwrought metal, waste and scrap.
[b] Metals imports is unwrought metal only; waste and scrap total 407 tons.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook*, vol. 1, 1970, 1974, and 1980.

1984 the picture was somewhat brighter owing to the steel industry revival. (Of the 14 furnaces some have been permanently decommissioned.) Elkem was awarded a contract by the General Services Administration (GSA) in the spring of 1984 to convert 48,476 tons of manganese ore in the national defense stockpile into ferromanganese.[104] This GSA plan to upgrade stockpiled ores was developed in late 1982 by the Reagan Administration to give financial relief to the domestic ferroalloy industry. The contract amount will, however, only provide about 6 months work for one Elkem furnace. (See the chromium processing section for details on a similar chromite conversion contract.)

Manganese metal, sufficient to cover domestic needs, can be produced in the United States, although the feedstock is imported manganese ores. In 1982 domestic production of manganese metal (18,600 tons) was greater than the consumption rate (17,100 tons),[105] while an additional 30 percent was imported. Due to general economic conditions, in 1983 two metal producing firms were operating at reduced levels of production and the third had shut down its facilities.

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[104] "Macalloy Sets Reorganization," *American Metal Market*, Jan. 5, 1984, p. 1.

[105] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982*, vol. 1, pp. 579-580.

Platinum Group Metals Production and Processing

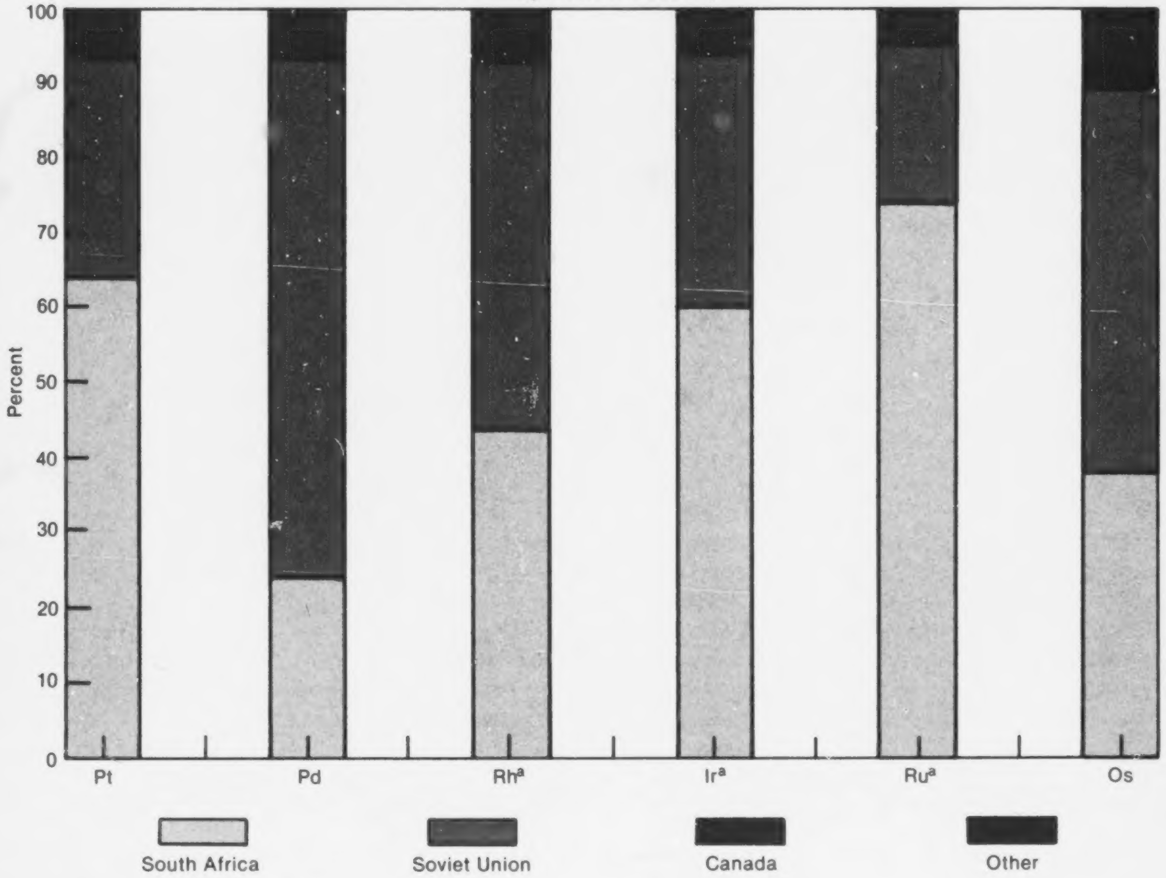
PGMs have always come from few locations. Colombian placer deposits were the original and only suppliers of PGMs until 1824, when Russian placer deposits were discovered. Prouction from Canadian nickel mines followed in 1919, and South African deposits were discovered in 1924. South Africa, the Soviet Union, and Canada are today the world's suppliers of these metals (see fig. 5-6).

The major deposits of this group of metals have been found in layered formations of igneous rocks among chromite, nickel, and copper. Only in South Africa and, it has been estimated, the United States (Stillwater, MT) can such vein deposits be mined primarily for their PGM content. Canada produces PGMs as a byproduct of nickel and copper production; the Soviet Union's production may be a coproduct rather than a byproduct. Chemical and physical weathering can separate platinum minerals from these primary ores, creating placer deposits in high enough concentrations to provide minable ore grades. Such a PGM deposit exists in Goodnews Bay, AK, but it has not been in production since 1975.

Each PGM deposit produces platinum and palladium and some of the other four metals (rhodium, ruthenium, iridium, and osmium) of the group. Among the similar sulfide deposits in the three producer countries, there are differences in the proportion of PGMs that each contributes to the market, as shown in table 5-34. Platinum and palladium are considered the most important metals of the group owing to their predominance and end uses in industry. While Canada produces roughly an equal

Figure 5-6.—Comparative PGM Production, 1981

By metal and country



[a] Less than 1 percent produced by other sources.

SOURCE: Bureau of Mines, *Minerals Commodity Profile 1983: Platinum-Group Metals*, figures 1 through 6.

amount of platinum and palladium, the Soviet Union's output is principally palladium (67 percent), with platinum secondary (25 percent). In South Africa, platinum accounts for 61 percent of production, and palladium, 26 percent. For all three countries, the balance of output is in small amounts of the minor metals of the group. The proposed Stillwater mine is expected to produce almost 80 percent palladium, 20 percent platinum. Colombia has long been a relatively small producer from placer deposits. Its output is over 90 percent platinum. Very small amounts of the metals are produced by a number of other countries as byproducts from a variety of ores. The United States is included in this group with a contribution from copper mining and refining.

The world now depends on South Africa for two-thirds of its platinum and on the Soviet Union for two-thirds of its palladium. In 1982, 99 percent of the world's primary PGM supply was produced by five private firms and one government firm. Mines in South Africa and the Soviet Union provide 95 percent of the world's needs, while Canadian mines provide another 6 percent (table 5-35). Little change in this pattern is likely in the future. The most

Table 5-34.—Distribution of Platinum Group Metal Production by Metal and Country, 1981 (percentage)

Producer country	Platinum	Palladium	Rhodium	Iridium	Ruthenium	Osmium
Canada	6	6	8	6	5	10
South Africa	64	24	44	60	74	38
Soviet Union	29	69	49	34	21	51
Other	1	1	<1	<1	<1	<1
Total	100	100	100	100	100	100

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Commodity Profile 1983: Platinum-Group Metals*, figures 1 through 6.

Table 5-35.—Platinum Group Metals: World Reserves and Production by Country (thousand troy ounces[a])

Producer country	Reserves 1981	Production 1982	Percent of world production
Australia		14.0	0.22
Canada	9,000	269.8	4.18
Colombia		12.0	0.19
Ethiopia		0.1	
Finland		3.6	0.06
South Africa	970,000	2,600.0	40.28
Soviet Union	200,000	3,500.0	54.23
United States	16,000	8.0	0.12
Yugoslavia		3.5	0.05
Other[b]		43.3	0.67
Total	1,200,000	6,454.3	100.00

[a] There are 14.58 troy ounces per pound.

[b] "Other production" reflects Japanese refining of ores originating in Australia, Canada, Indonesia, Papua New Guinea, and the Philippines.

SOURCE: Reserve base—*U.S. Department of the Interior, Bureau of Mines, Mineral Commodity Profile 1983: Platinum-Group Metals.*
Production—U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982*, vol. 1.

activity underway in investigating new, diversifying sources is in the United States with the effort to initiate mining from the deposits at Stillwater. For possible long-term applicability, the U.S. Geological Survey is conducting research on the platinum content of nickel laterite deposits in countries along the southwestern rim of the Pacific Ocean.

The principal importing nations are the United States and Japan, which together consume about two-thirds of the world's PGM production. Western Europe and the Soviet Union consume most of the remainder. The Soviet Union's position as the important palladium supplier to the West provides it with one of its valuable sources of foreign exchange, although gold sales are more important in this respect.

Foreign Production of Platinum Group Metals

Unlike many other mineral industries today, PGM production, excluding that of the Soviet Union, is entirely within the private sector. Ownership is a complex interconnection of multinational firms, as shown in table 5-36.

Rustenberg Platinum Mines and Impala Platinum Holdings control over 90 percent of South African production. Ownership of both firms is primarily local shareholders, through three investment houses. These "group" houses have connections with British industry that date back to colonial times. They also hold interests in American operations: Johnson Matthey—which jointly owns a South African refinery with Rustenberg (Matthey-Rustenberg

Table 5-36.—PGM Mining Industry by Country

Country	Major firms	Ownership		
		Sector	Major holders[a]	Primary national identity
Canada	Inco Ltd.	Private	[b]	Canada
	Falconbridge Ltd.	Private	McIntyre Mines[c] (40)	Canada
		Private	Newmont Mines[d] (40)	U.S.
South Africa[e]	Rustenberg Platinum Mines Ltd.	Private	JCI[f] (33)	Local
		Private	AngloAmer (24)	Local/U.K.
		Private	Ludenburg (24)	Local
	Impala Platinum Holdings Ltd.	Private	Gencor (56)	Local
	Western Platinum Ltd.	Private	Lonrho (51)	Local/U.K.
		Private	Falconbridge (25)	Canada/U.S.
		Private	Superior Oil (24)	U.S.
Soviet Union		Government	(100)	
United States[g]	Goodnews Bay	Private	Hansen Properties	U.S.
	Stillwater Mining Co.	Private	Johns-Manville	U.S.
		Private	Chevron Resources (Chevron USA)	U.S.
		Private	Anaconda Minerals (Atlantic Richfield)	U.S.

[a] With approximate percentage of control, if available.

[b] The largest, single-shareholder block of Inco stock is 4 percent.

[c] Falconbridge is 32.7 percent owned by Superior Oil through direct equity and its controlling interest in McIntyre.

[d] Newmont Mining (22%) owned by Consolidated Gold Fields (U.K.), which is (29%) owned by Minerals & Resources Corp., which is (43%) owned by Anglo American.

[e] There are six finance houses (the "Groups") which dominate the South African industry: The Anglo American Corp. of S.A. Ltd. (AngloAmer); Gold Fields of S.A. Ltd.; General Mining Union Corp. Ltd. (Gencor); Rand Mines/Barlow Rand; Johannesburg Consolidated Investment Co. Ltd. (JCI); and Anglo-Transvaal Consolidated Investment Co. Ltd. (AngloTC).

[f] Johannesburg Consolidated Investment Co. Ltd. is (41%) owned by the Anglo American.

[g] Not in production, prospective only.

SOURCES: E&MJ *1983 International Directory of Mining;* Bureau of Mines, *Mineral Commodity Profile 1983: Platinum-Group Metals*; Office of Technology Assessment.

Refiners)—and Engelhard Corp., both with refineries in England and the United States, are connected through Minerals & Resources Corp. to the Anglo American Corp. of South Africa, one of the group houses. The third South African producer firm, Western Platinum, is controlled by British, Canadian, and American interests.

Canada's two PGM-producing firms are primarily Canadian and American owned. Falconbridge, which is a part owner of Western Platinum in South Africa, owns a refinery in Norway. Inco operates refineries in Canada and the Mond Nickel Co. refinery in England.

While most of the mining firms are vertically integrated, from ore mining and processing through to metal production, processing has traditionally involved a physical, international flow of semiprocessed forms of the metals between mining countries and refiners in northern Europe. While Rustenberg now has the capability to process its ores completely within South Africa, some still follow the traditional path and are shipped as concentrates or in smelted form (matte) to England for refining. Western Platinum ships mixed metal mattes to Norway, where nickel and cobalt are extracted. Final PGM units (as a "sludge") are returned to South Africa for final separation. Canada's Inco ships PGM sludge to its plant in England for refining. Falconbridge's semiprocessed ores go to Norway, with final recovery either in Norway or at the Engelhard refinery in Newark, NJ.

A consequence of this processing flow of PGMs is that essentially all the United States' primary PGM needs, even those obtainable from Canada, must ultimately be shipped from overseas. Both Ontario and Manitoba provinces in Canada have laws requiring all ores mined there to be fully processed in Canada, if possible. Inco and Falconbridge have so far been granted exemptions allowing them to export semiprocessed ores for refining, following a pattern set more than 50 years ago. Both expect to continue this system as long as it is economically feasible to use their northern European refineries. While semiprocessed ores are transported by surface, final metal forms are normally shipped by air, mitigating potential access problems (on the return journey) during crises.

Platinum group metals are investment as well as industrial commodities. Accordingly, three levels of trade exist: long-term contracts between producers and consumers, the dealer market for small and spot purchases, and investment and speculative buying of futures contracts on various metal exchanges, such as the New York Merchantile Exchange (platinum and palladium) and the Japanese Gold Exchange (platinum). At any one time, stocks of these metals are held by producers, refiners, investors, dealers, fabricators, and governments. The U.S. Bureau of Mines estimated that at the end of 1981 there were 900,000 troy ounces of PGMs (about a 4 to 5 months' supply) held by these groups in the United States alone.[106] The existence of widespread holdings of these stocks is one factor used to explain why the producer-set price recently gave way —after a 50-year dominance—to a market price for PGMs. In effect, the stocks held by a variety of groups serve as an intermediate supply, reducing producers' ability to set prices or control the flow of processed material.

Any near-term increase in demand is expected to come from current sources. South African producers, who tend to tailor production to their estimates of western consumption, have proven adept in drawing on their vast reserves to meet increased demand. In the 1970s, for example, South African firms greatly expanded production to meet demand created by requirements for automobile catalytic converters in the United States. They would likely respond similarly in the future, and their ample resources should allow them to do so.[107] Most of South Africa's production of PGMs is committed to major consumers—including the automobile industry (for catalytic converters)—through long-term (approximately 10-year) contracts. While information about contracts is not made public, Rustenberg reportedly supplies Toyota, Honda, and Ford; Impala is said to supply General Motors, Chrysler, and Nissan; and Western Platinum reportedly supplies Mitsubishi.[108]

While South Africa's portion of the world PGM market has steadily increased, Canada's production has not kept pace with growing demand. Since the 1960s, its share of the world market has decreased by 84 percent, while actual output has remained level.

The Soviet Union's production and marketing techniques cannot be determined accurately; most of its output is marketed through dealers rather than directly. Explanations for short-term changes in the amount of palladium made available for the market have ranged from pure political motivations to maximization of long-term commercial advantage. Over the past 20 years, the Soviets have managed to increase steadily the overall production of PGMs.

The following country-by-country overview of major producers discusses the current and projected status of PGM output.

Canada

Inco is the major PGM producer in Canada, with Falconbridge a distant second. Both derive PGMs as byproducts of nickel-copper sulfide deposits near Sudbury, Ontario. Inco also has lesser deposits at Thompson, Manitoba. PGM processing is tied to recovery of nickel, copper, and cobalt. Inco's ores are smelted at Copper Cliff, Ontario, with final recovery of PGMs at the firm's Mond Nickel Co. refinery at Acton, England. Falconbridge smelts ores in Sudbury; ships a nickel-copper matte to its plant in Norway for nickel, copper, and cobalt recovery; and refines the resulting PGM sludge in Norway or at the Engelhard refinery in Newark, NJ.

South Africa

In South Africa, PGMs are considered the primary product derived from sulfide deposits. Rustenberg Platinum Mines produces more than 50 percent of South Africa's output, followed by Impala, with some 40 percent. The balance is produced by Western Platinum, which now has capacity to produce about 125,000 troy ounces of platinum per year. The Bushveld Complex in northeastern South Africa supports the entire PGM production. PGM deposits primarily occur in its Merensky Reef section—with concentrations ranging from 4 to 15 grams per tonne of ore or 4 to 15 parts per million (ppm). (Technically, 9 percent of South Africa's PGM reserves lie within the Bophuthatswana Homeland. Bophuthatswana actually produced over half of the PGMs credited to South Africa in 1982 as all of Impala's mining operations are within the homeland along with part of Rustenberg's.)

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[106] U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Profile 1983: Platinum-Group Metals*, p. 10.

[107] See for instance, the Bureau of Mines' *Platinum Availability—Market Economy Countries*, Information Circular No. 8897/1982.

[108] "Impala, GM Set Long-Term Pact Huddle," *American Metals Market*, June 2, 1983.

Two other sections of the Bushveld, the Upper Group (UG2) Chromium seam and the Platreef, have lower overall grades of PGMs but higher proportions of some of the lesser metals, such as rhodium and ruthenium. The Platreef is currently unmined. Western Platinum produces from some sections of the UG2. With the introduction of a new smelting process in 1984, PGMs can also be extracted from the chromite seams. The Bureau of Mines has stated[109] that commercial development of the UG2 and Platreef of the Bushveld Complex would more than double the amount of platinum available from South African deposits.

Rustenberg and Impala each have facilities in South Africa to process their ores completely to metal forms of separated PGMs. Rustenberg can also ship semiprocessed ores to the Johnson Matthey plant at Royston, England, for processing. Western Platinum ships all its production as mixed metal mattes to the Falconbridge (a part owner of Western) plant in Norway for separation of copper, nickel, and cobalt. A residual PGM sludge is returned to the Lonrho refinery at Brakpan in South Africa for final separation of PGMs. Western is currently considering development of its own matte treatment facility in South Africa, which—if established—would eliminate the time-consuming shipment of matte to Norway, cutting overall PGM processing time from about 6 to 2 months.

Gold Fields of South Africa Ltd. (partly owned by Consolidated Gold Fields of London, which is 30-percent owned by Anglo American) has been investigating a prospective new PGM mine on the Merensky Reef. The project was in the exploration phase in 1984. Potential PGM output is expected to total 386,000 troy ounces, including platinum (64 percent), palladium (27 percent), ruthenium (6 percent), and rhodium (3 percent). This would add about 5 percent to the world's output of PGMs (using 1980 as a base year).

Soviet Union

PGMs are a coproduct or byproduct derived from nickel-copper sulfide deposits in Siberia (with PGM values as high as 10.4 grams per tonne of ore) and the Kola Peninsula. Limited amounts are also produced from placer deposits in the Ural Mountains. The mines at the Noril'sk mining combine in Siberia provide up to 90 percent of the total output. Ores, extracted under adverse conditions of an 8-month winter, are smelted and refined to metal within the Soviet Union. Expansion of capacity at Noril'sk, reportedly underway in the 1980s, could significantly increase Soviet production capabilities.

Potential Foreign Sources

The U.S. Geological Survey has a study underway to determine the PGM content of laterite formations in the Southwest Pacific (Indonesia, the Philippines, and New Caledonia). These mineralizations are found along with chromite. The separation techniques using plasma technologies that are being developed in South Africa for PGM/chromite deposits there could be applicable. The economic feasibility of mining PGM in these laterite formations may make it possible to extract the chromite content as a byproduct.

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[109] T. F. Anstett, et al., U. S. Department of the Interior, Bureau of Mines, *Platinum Availability—Market Economy Countries*, Information Circular No. 8897, 1982, p. 12.

Domestic Production of Platinum Group Metals

In contrast to the other first-tier materials, the United States is a producer, albeit minor, of PGMs (8,033 troy ounces in 1982 as a by-product of copper mining and refining) and mining firms are actively pursuing the commercial possibilities of exploiting PGM deposits at Stillwater in Montana. These deposits could initially supply 14 percent of the U.S. palladium and 4 percent of platinum needs, or 9 percent of overall PGM needs (based on 1982 consumption data). Production from Stillwater is considered to be the only possible near-term, worldwide competition for existing PGM producers such as South Africa and the Soviet Union.

The Goodnews Bay Placer Mine in Alaska is a past producer of PGMs and was to resume operations in mid-1981 but did not. There are no immediate plans to do so. Other U.S. PGM resources exist in Alaska (Salt Chuck Mine and the Brady Glacier-Crillion-Le Pousse sulfide deposit) and Minnesota at the Duluth Gabbro. These latter properties have not been the subject of any recent commercial development interest. New U.S. mining activity in the development and expansion of gold and silver properties (the ore bodies of which often contain some PGMs) may result in small amounts of PGMs being recovered.

U.S. resources of PGM total 300 million troy ounces (less than 10 percent of world resources) and are concentrated in Montana, Alaska, and Minnesota.[110] An estimate of total possible U.S. production of PGMs from the most likely properties—Stillwater, Goodnews Bay, and the Duluth Gabbro—is shown in table 5-37.

Stillwater Complex, MT

PGM occurrences in the Stillwater Complex along the Beartooth Mountains in Montana have been commercially explored and evaluated over the past 15 years. The deposits are geologically similar to those in the Merensky Reef of South Africa and contain nickel, copper and chromite in addition to PGMs. Stillwater is being evaluated on the basis of extracting PGMs from sulfide ores as a primary product. The Complex is approximately 28 miles long and from 1 to 5 miles wide and is divided into distinctive mineralized zones with PGMs present at greater-than-normal concentrations in some bands. Typical PGM grades at Stillwater have been reported by the Bureau

Table 5-37.—Potential U.S. PGM Production

Resource/mine	Estimated annual production capacity (troy ounces of contained metal)		Estimated minelife (years)	Production dependent on
Stillwater, Montana			10-25	Combined platinum-palladium price of about $220 per troy ounce (1984)[a]
Initial:	Palladium	136,000		
	Platinum	38,000		
	Total	175,000		
Additional expansion:	Palladium	340,000		
	Platinum	97,000		
	Total	437,000		
Goodnews Bay, Alaska			unknown	Platinum price of $600-700 per troy ounce (1984)
	Platinum	10,000		
Duluth Gabbro, Minnesota			25	Copper, $1.50 per pound
	Palladium	30,800- 92,400		Nickel, $4.00 (1975 data converted to January 1983 dollars)
	Platinum	6,800- 20,300		
	Total	37,600-112,700		

[a] Year of estimate.

SOURCE: Stillwater—Stillwater Mining, June 1984.
Goodnews Bay—Hanson Properties, July 1984.
Duluth Gabbro—Calculated by OTA using preliminary results of Bureau of Mines research on Duluth ores; State of Minnesota, *Regional Copper-Nickel Study*, 1979; Silverman, et al., OTA background study, 1983.

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[110] J. Roger Loebenstein, U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Profiles 1983: Platinum-Group Metals*, p. 3.

of Mines as 0.130 troy ounces of platinum and 0.509 troy ounces of palladium per ton of ore (5 ppm platinum, 17 ppm palladium). In comparison, grades of representative ore from the Merensky Reef are 0.154 troy ounces of platinum and 0.066, palladium per ton (5 ppm platinum, 2 ppm palladium).[111] The estimated PGM reserves of the entire complex have been reported at 7 million troy ounces.[112]

The most important PGM zone was discovered during exploration by the Johns Manville Sales Corp. in 1967 and sparked renewed commercial interest in this area once mined for its chromite content. The Johns Manville zone has an estimated 0.47 troy ounces of platinum and palladium per ton of ore with a palladium-to-platinum ratio of 3.5:1[113] (0.11 troy ounces of platinum and 0.36 troy ounces of palladium per ton of ore, or 4 ppm platinum and 12 ppm palladium).

Two sets of properties in the Stillwater Complex have been the object of extensive commercial exploration since 1979. The properties, since June 1983, have been held by a joint venture of Stillwater PGM Resources & Anaconda Minerals Co. under the name of Stillwater Mining Co. Stillwater PGM Resources is a partnership of Johns-Manville and Chevron Resources Co. (Chevron USA); Anaconda Minerals is a wholly owned subsidiary of Atlantic Richfield. Stillwater Mining Co. has selected a particular mineralized zone (the Minneapolis Adit) in one of the original Anaconda properties as the site for an 18-month exploration and evaluation effort. Core drillings, both from the surface and within the Adit, constitute a major portion of the evaluation project's data. This joint project may—or may not—result in eventual combined mine development and production activity.

The development phase would reportedly take 2 years to place into operation an underground, hard-rock mine producing 1,000 tons of ore per day. A milling plant, constructed at the mining site, would produce a concentrate from the mined ores by grinding and flotation processes. This product would be transported by surface to an existing smelter (e.g., Inco's in Canada) for refining. Estimated mine life for the project is 20 years.[114]

In mid-1984, the possibility of proceeding with mining development was considered "very price sensitive."[115] A weighted average price of $220 per troy ounce of PGMs is being used in Stillwater Mining's feasibility study calculations. (As a comparison, the June 1984 producer prices for PGMs were: platinum, $475 per troy ounce and palladium, $130 to $140.[116] At these prices and given the Stillwater palladium-to-platinum ratio of 3.5:1, a weighted average price of $206 to $214 is realized. Thus, the market prices did not quite meet the target price.) The drilling program and feasibility study is scheduled for a mining development "go/no go" decision by mid-1985.

Anaconda's Stillwater Project had originally proposed, for a 1982 draft EIS, a mining operation producing 350,000 tons of ore per year (1,000 tons daily for 350 days per year) over 25 years. Contained PGMs (at about 0.5 troy ounces per ton of ore) would be 500 troy ounces per day (or 175,000 troy ounces per year).[117] The Anaconda site (now the Stillwater Mining investigation) is smaller than the original Stillwater PGM Resources properties, whose reserves might be able to support a mining rate of 2,500 tons of ore per day,[118] or approximately 437,500 troy ounces per year of contained PGM values.

The Stillwater Complex is located in a rural, agricultural community, partly within the borders of two national forests. While development of mining at Stillwater would provide job opportunities and broaden the local tax base, local citizen groups have voiced concerns over population influx, overburdening of the public service system and environmental issues such as location of the mill and tailings pond, the wastewater's effect on the region's groundwater, and protection of air, water and wildlife. During any permitting process, Montana's Department of State Lands will coordinate the preparation of the necessary EIS; and the local government and the Montana Hard Rock Mining Impact Board will evaluate socioeconomic issues.

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[111] Ibid., p. 4.

[112] Anstett, et al., op. cit., p. 7.

[113] *The Stillwater Citizen-Sun*, Apr. 26, 1984, sec. 2, p. 5.

[114] *The Stillwater Citizen-Sun*, p. 12.

[115] Les Darling, Environmental Coordinator and principal spokesperson, Stillwater Mining Co., personal communication, May 1984.

[116] "Closing Prices," *American Metal Market*, June 15, 1984, p. 31.

[117] Silverman, et al., op. cit., p. 104 (text of EIS).

[118] Silverman, et al., op. cit., p. 190. A Sept. 10, 1980, statement from the Manville group estimated a production rate of 1,000 to 3,000 tons of ore per day.

Goodnews Bay and Other Alaska Occurrences

The Goodnews Bay Placer Mine is a dredging operation located on the Salmon River near the Bering Sea coastline of Alaska. Production from Goodnews Bay totaled 641,000 troy ounces of PGMs (over 80 percent platinum) from 1934 until 1975, when production was halted.[119] Although new owners, Hanson Properties, announced intentions to resume operations in 1981, operational difficulties with dredging machinery, environmental issues, and overall, the costs of production have prevented them from doing so.[120]

While the major component of this placer deposit is platinum (reserves are estimated at 500,000 troy ounces of platinum),[121] other PGMs and precious metals are present. The approximate proportions of metals in the concentrate produced in the past were 82.31 percent platinum; 11.28, iridium; 2.5, osmium; 0.17, ruthenium; 1.29, rhodium; 0.38, palladium; and 2.24 percent gold.[122] The mine could possibly produce up to 10,000 troy ounces of platinum per year.[123] The high grade concentrate generated could be shipped directly to a U.S. refinery, such as Engelhard in Newark, NJ, for processing.

The Salt Chuck lode mine has been intermittently exploited for various PGMs since 1918 with the latest period of operation having been 1935 to 1941. Overall, 14,271 troy ounces of PGMs have been produced from this mine.

PGMs are known to exist in deposits in Glacier Bay National Park in the Crillion-La Perouse Complex. An unpublished U.S. Geological Survey report in 1980 indicated that platinum may be recovered as a byproduct from the Brady Glacier nickel-cooper ore body. The ore body, which extends under moving glacier ice, has not been extensively evaluated and could prove expensive to mine.[124] In addition, given its location, environmental concerns would weigh heavily on any mining prospects.

In general, there is potential for more lode and placer deposits in Alaska. The Alaska Field Operations Center of the Bureau of Mines has an ongoing program specifically directed toward improving the available information about occurrences of PGMs, as well as chromite and cobalt, in Alaska.

Duluth Gabbro, Minnesota

Copper and nickel sulfide deposits along the Duluth Gabbro in the Lake Superior region of northeastern Minnesota contain cobalt, PGMs and other precious metals that could be recovered as byproducts. Production of significant amounts of PGMs depends on copper and nickel mining on a large enough scale to make these low-grade resources competitive in global markets. Commercial production will not even be considered until the recovery of both primary metals markets occurs and existing worldwide nickel and copper mines have returned to full production. (For information on the economics of Duluth Gabbro and a Regional Cooper-Nickel study released in 1979 by the State of Minnesota, see the domestic cobalt section.)

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[119] James C. Barker, et al., U.S. Department of the Interior, Bureau of Mines; *Critical and Strategic Minerals in Alaska: Cobalt, the Platinum-Group Metals and Chromite*, Information Circular No. 8869, 1981, p. 2.

[120] Raymond Hanson, Hanson Properties, personal communication, July 1984.

[121] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1981*, p. 668.

[122] These are the weighted mean percentages of the metals mined from Goodnews Bay from 1936 to 1970 as presented in the National Research Council, National Materials Advisory Board, *Supply and Use Patterns for the Platinum-Group Metals*, NMAB-359, 1980, p. 17.

[123] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook, 1981*, vol. I, p. 668. Mr. Hanson inferred that this figure was high and commented that it was "what the oldtimers in Alaska claim."

[124] *Critical and Strategic Minerals in Alaska*, op. cit., p. 3.

Photo credit: Hanson Properties, Inc.

Platinum was recovered from the placer deposits at Goodnews Bay, Alaska from 1937 to 1976. Higher prices for platinum group metals could result in reactivation of the mining camp (top) and the mining dredge (bottom)

Industry interest in the area peaked between the late 1960s and 1970s. During that time, Amax Nickel acquired an option from Kennecott Copper and investigated the possibility of a combined surface and underground operation (Minnamax) and Inco considered opening an open pit mine (Ely Spruce). Inco's project was suspended in 1975, and Amax indefinitely postponed its project in 1981 owing to depressed metal prices. This property has now reverted back to Kennecott control. There has been no revival of commercial interest in the area.

These two holdings in the Duluth Gabbro contain demonstrated resources of less than 800,000 troy ounces of platinum.[125] PGM values of 0.00107 troy ounces of platinum and 0.00304 troy ounces of palladium per ton (0.036 ppm platinum, 1.03 ppm palladium) were estimated from an Inco sample by the Bureau of Mines.[126] The Minnesota Department of Natural Resources extrapolated this data to the rest of the area and estimated that about 18 million troy ounces of platinum resources existed in 4.4 billion tons of ore.[127]

The Bureau of Mines has recently conducted research on the processing of raw materials typical of Duluth Gabbro ores, and a report on the results is in preparation. Data from these studies indicate that, under optimum conditions, the recovery of platinum and palladium per ton of ore would be approximately 0.0005 troy ounce and 0.0022 troy ounce, respectively. This is equivalent to approximately 0.088 troy ounces of platinum and 0.40 troy ounces of palladium per ton of copper produced.[128] In the 1979 study by the State of Minnesota, the maximum possible annual output from Duluth was calculated at 231,000 tons of copper metal and, with one mine complex (rather than three) in operation, 77,000 tons of copper would be produced per year. This implies that between 30,800 and 92,400 troy ounces of palladium and between 6,800 and 20,300 troy ounces of platinum might be generated as byproducts from Duluth given the proper economic incentives for copper and nickel production.

Although the Duluth Gabbro lacked any commercial activity recently, this large resource of low-grade material will continue to be viewed as a potential source of metals. The proximity of potential mining areas to the Boundary Waters Canoe Area and Voyageurs National Park, as well as possible damage from sulfur emissions from a smelter operation processing Duluth Gabbro sulfide ores, will ensure an important role for environmental considerations in mine planning in the area.[129]

Domestic Mining and Processing Technology Prospects

PGM deposits which occur in hard-rock environments (Stillwater, for instance) are amenable to underground methods such as sublevel stoping and the newer vertical crater retreat system. Placer deposits are generally dredged unless, as may be the case in some areas of the Goodnews Bay deposit in Alaska, the thickness of the overburden makes the technique uneconomic.

Domestic PGM deposits are not unique and, therefore, metallurgical processing technology is available. The high-grade platinum concentrates from Goodnews Bay can be sold directly to existing U.S. precious metal refineries for purification. Technology for the required smelting and refining of Stillwater's nickel-copper-PGM ores is well established. The most qualified North American smelter for the initial refining of its concentrates is the Inco plant at Copper Cliff, Ontario.

Included in current Bureau of Mines research is the evaluation of a method for processing of Stillwater ores. It involves flotation of the ores and subsequent smelting and leaching to recover the various metal values in the ores. The flotation concentrate results in 88 percent recovery of the PGM values and smelting to a sulfide matte retains 95 percent, for an overall recovery of 84 percent. This matte then requires a refining step to separate out PGMs and gold.[130] Duluth ores are also under investigation and are discussed in the preceding domestic cobalt section.

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[125] Anstett, et al., op. cit., p. 7.

[126] National Research Council, National Materials Advisory Board, *Supply and Use Patterns for the Platinum-Group Metals,* NMAB-359, Washington, DC, 1980, p. 16.

[127] Ibid., p. 16.

[128] U.S. Department of the Interior, Bureau of Mines, letter to OTA, July 31, 1984.

[129] Silverman, et al., op. cit., p. 112.

Processing of Platinum Group Metals

The major end uses of PGMs are as catalysts in the automotive, petrochemical, and chemical industries and as contacts in the electronics industry. These products are fabricated from chemical forms of PGMs, which are produced from metals, mainly platinum and palladium and, increasingly, rhodium.

PGMs follow the same processing path as cobalt because they originate in the same ores. PGMs are the last step in the long extraction process of these ores (fig. 5-7), and it can take up to 6 months to complete the cycle from mining of the ores to production of PGMs. The final residual from the sequential processing is a PGM concentrate, or "sludge." Separation of the precious metals from this concentrate is accomplished by various chemical methods, many of which are proprietary. A new extraction process developed by the South African National Institute of Metallurgy in 1975 can reduce the overall PGM processing time dramatically (to 20 days). Two South African refineries and one in England now use the institute's process.

PGMs are imported by the United States in forms such as unwrought and semimanufactured metal. Recycled catalysts from the petroleum and chemical industries are another source. The processing industry in the United States consists of refiners and fabricators. Large firms, such as Engelhard and Johnson Matthey, can handle the final PGM processing steps, while smaller firms only fabricate the end products. Engelhard's New Jersey refinery reportedly processes some of Falconbridge's (Canada) PGM sludge. The National Materials Advisory Board reported in 1980[131] that, as a whole, the U.S. PGM processing industry was healthy and aggressive and could readily meet the challenges of any increased demand.

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[130] *Research 83*, op. cit., p. 89.

[131] NMAB-359, op. cit.

Exploration

The development of the major known domestic resources of chromium, cobalt, manganese, and PGMs is technically feasible if political necessity dictates. However, with the exception of a PGM deposit, these domestic resources could be produced only at several times current world price.

Exploration for additional domestic deposits by private concerns will proceed only insofar as there are geologically favorable areas, perceived economic benefits to the explorer, and procedures that permit mining if a discovery is made. No group is actively exploring for first-tier strategic materials in the United States today. The benefits are not consistent with the costs and risks involved, especially when foreign countries can produce vast quantities of high-grade materials at costs well below that of any domestic producer.

Land-Based Resources[132]

In North America, Precambrian rocks are considered the most geologically favorable areas for possible significant deposits of chromite and nickel-copper-cobalt sulfides with associated PGMs. Figure 5-8 shows the formation period (1 to 2.6 billion years ago) of certain world deposits of chromium, cobalt and PGMs. The formation of manganese deposits is not as exclusively timebound as the other

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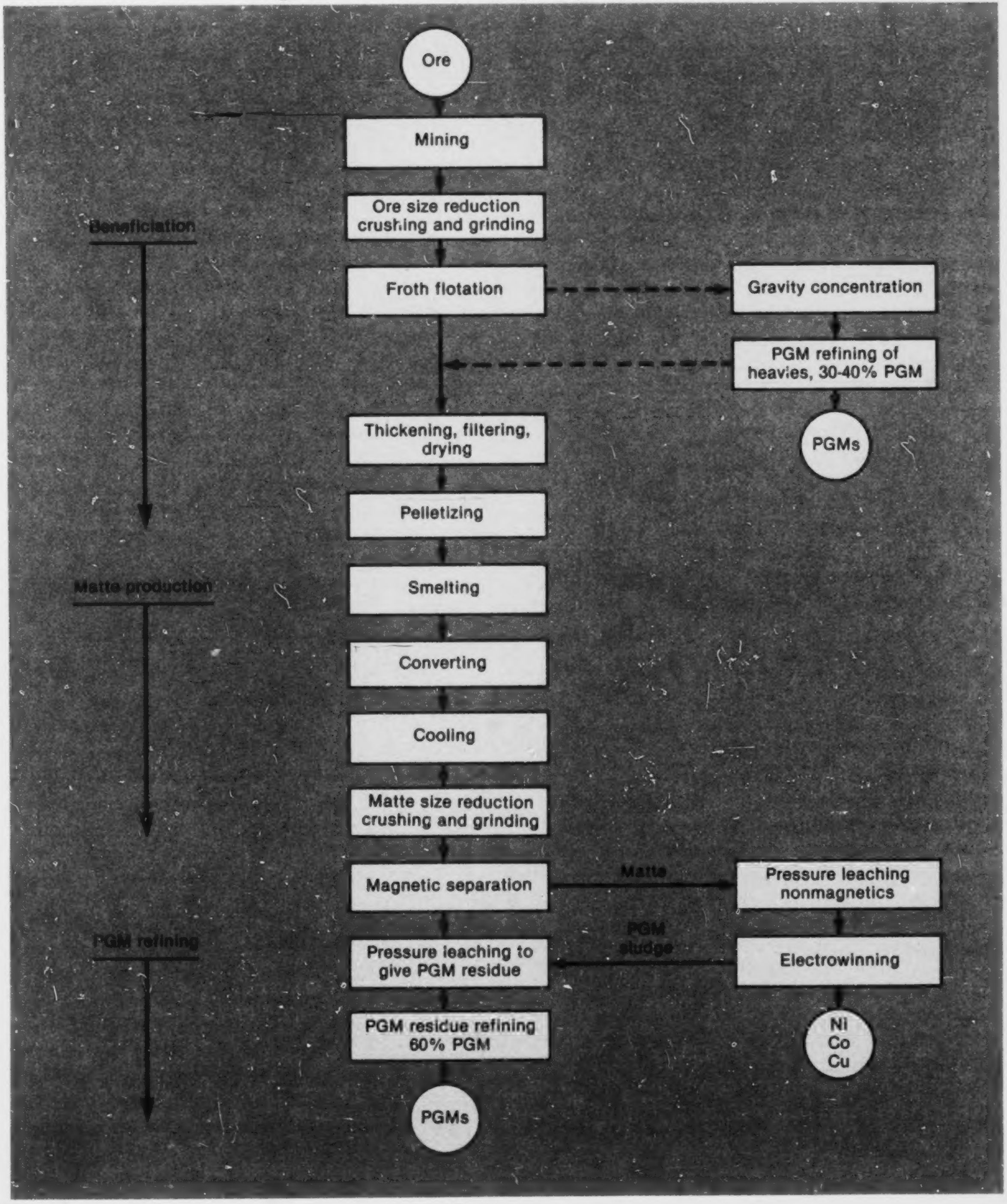
[132] This section is based primarily on Ben F. Dickerson III, and Carole A. O'Brien, *Exploration for Strategic Materials*, contractor study prepared for the Office of Technology Assessment, September 1983.

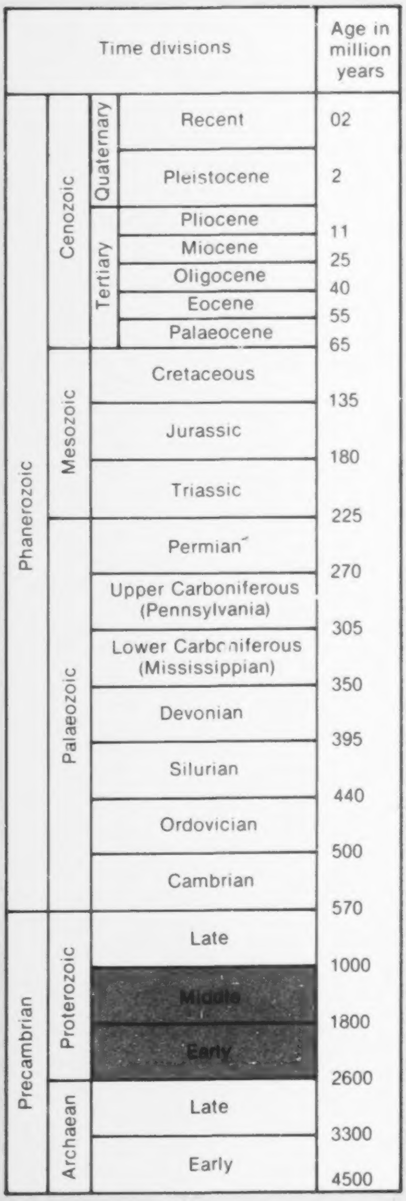
Figure 5-7.—PGM Processing, Simplified Flowchart[a]


Ore
Mining
Beneficiation
Ore size reduction crushing and grinding
Froth flotation
Gravity concentration
PGM refining of heavies, 30-40% PGM
PGMs
Thickening, filtering, drying
Pelletizing
Matte production
Smelting
Converting
Cooling
Matte size reduction crushing and grinding
Magnetic separation
Matte
Pressure leaching nonmagnetics
PGM refining
PGM sludge
Pressure leaching to give PGM residue
Electrowinning
Ni
Co
Cu
PGM residue refining 60% PGM
PGMs

[a] Typical South African process.

SOURCE: Department of the Interior, Bureau of Mines, *Platinum Availability—Market Economy Countries*, Information Circular #8897, 1982.

Figure 5-8.—Time Chart of Some First-Tier Strategic Material Deposits


Time divisions
Age in million years
Phanerozoic
Cenozoic
Quaternary
Recent
02
Pleistocene
2
Tertiary
Pliocene
11
Miocene
25
Oligocene
40
Eocene
55
Palaeocene
65
Mesozoic
Cretaceous
135
Jurassic
180
Triassic
225
Palaeozoic
Permian
270
Upper Carboniferous (Pennsylvania)
305
Lower Carboniferous (Mississippian)
350
Devonian
395
Silurian
440
Ordovician
500
Cambrian
570
Precambrian
Proterozoic
Late
1000
Middle
1800
Early
2600
Archaean
Late
3300
Early
4500

Deposit	Location	Approx. Age (million yrs.)	Commodity
Katanga	Zambia-Zaire		Cobalt
Duluth Gabbro	Minnesota	1000-1800	Nickel-Cobalt
Sudbury	Ontario	1000-1500	Nickel-Copper-Platinum
Bushveld	S. Africa	2000-2100	Chromite-Platinum
Outokumpu	Finland	2000-2100	Copper-Nickel-Cobalt
Kemi	Finland	1800-2300	Chromite
Stillwater	Montana	2400-2500	Chromite-Platinum
Great Dyke	Zimbabwe	2600-2700	Chromite-Platinum
		2400-2500	

SOURCE: Ben F. Dickerson III and Carole A. O'Brien, *Exploration for Strategic Materials*, contractor study prepared for the Office of Technology Assessment, September 1983.

strategic metals. In the United States the major exposure of Precambrian rocks (fig. 5-9) is in the Great Lakes region of Michigan, Minnesota, and Wisconsin, with smaller, scattered areas in many States, including Montana, Idaho, Colorado, Arizona, South Dakota, Wyoming, Texas, and Missouri.

The constraints on exploration imposed by the absence of extensive geological exposure cannot be ignored in assessing the Nation's strategic materials outlook. Currently unidentified geologic environments in the United States could possibly contain these metals, but the uncertainties involved in identifying such environments compound the already high risk of exploration of regions of known potential.

Metals experts interviewed by OTA generally agree that there is a very low probability that the United States contains significant, undiscovered economic deposits of chromite, cobalt, or PGMs. (Prospects for manganese are deemed somewhat better.) Undoubtedly, some geologists disagree with this majority opinion, asserting that increased geologic knowledge, better technology, and fresh exploration concepts can find new, economical deposits. Even if such deposits do exist, the apparent risk/reward ratio and the magnitude of identified foreign reserves preclude meaningful action under current conditions.

Experts were unanimous on one point: all believed their companies' management would reject any strategic metals exploration program, no matter how geologically well-conceived, now and in the near future.[133]

Until reliable long-term economic incentives (perception of profits commensurate with risks) are available, there will be no significant exploration for strategic materials in the United States. A recent estimate gave $290 million as the cost to find an ore deposit that would significantly affect the profits of a medium-sized corporation.[134] Any find would have to result in ores of higher than average grades and/or lower than average costs to mine, substantial and dependable markets, and an assumption of long-term stability in the domestic economy.

Exploration Technology Today and in the Future

The following briefly reviews present and potential near-term technological developments in land-based exploration for strategic materials. It is felt that the technology level that mineral geologists employ today is about 20 years behind the level used in oil and gas exploration. This may be a reflection of the value of national energy versus mineral needs. For instance, in 1977 fuel production in the United States was valued at $56.2 billion and metals production, a tenth of the fuels value at $5.2 billion.[135]

Most specialists think that a breakthrough in mineral exploration technology is unlikely in the next 10 years and that the exploration scene of the early 1990s will probably not be greatly different from that of today, except it will be more expensive. Current tools and techniques will be more precise and refined, owing largely to the application of mineral exploration advances, general scientific knowledge, and electronic technology. Lacking incentives to explore for strategic materials, there will be little attention to the development of specialized technology for that purpose; but any general improvements in exploration methodology or technology could be of use.

Chromite deposits, for instance, have generally been found by surface prospecting and drilling in and around identified outcrops (surface appearances). There are no unique problems in exploring for most types of cobalt deposits. Current geophysical methods can be used to detect the presence of copper, nickel and iron sulfide minerals, with which it is associated. Cobalt can be easily identified by relatively simple chemical analysis methods.

GENETIC THEORY

Increased interaction between industry and academia could lead to better application of new and developing concepts in genetic the-

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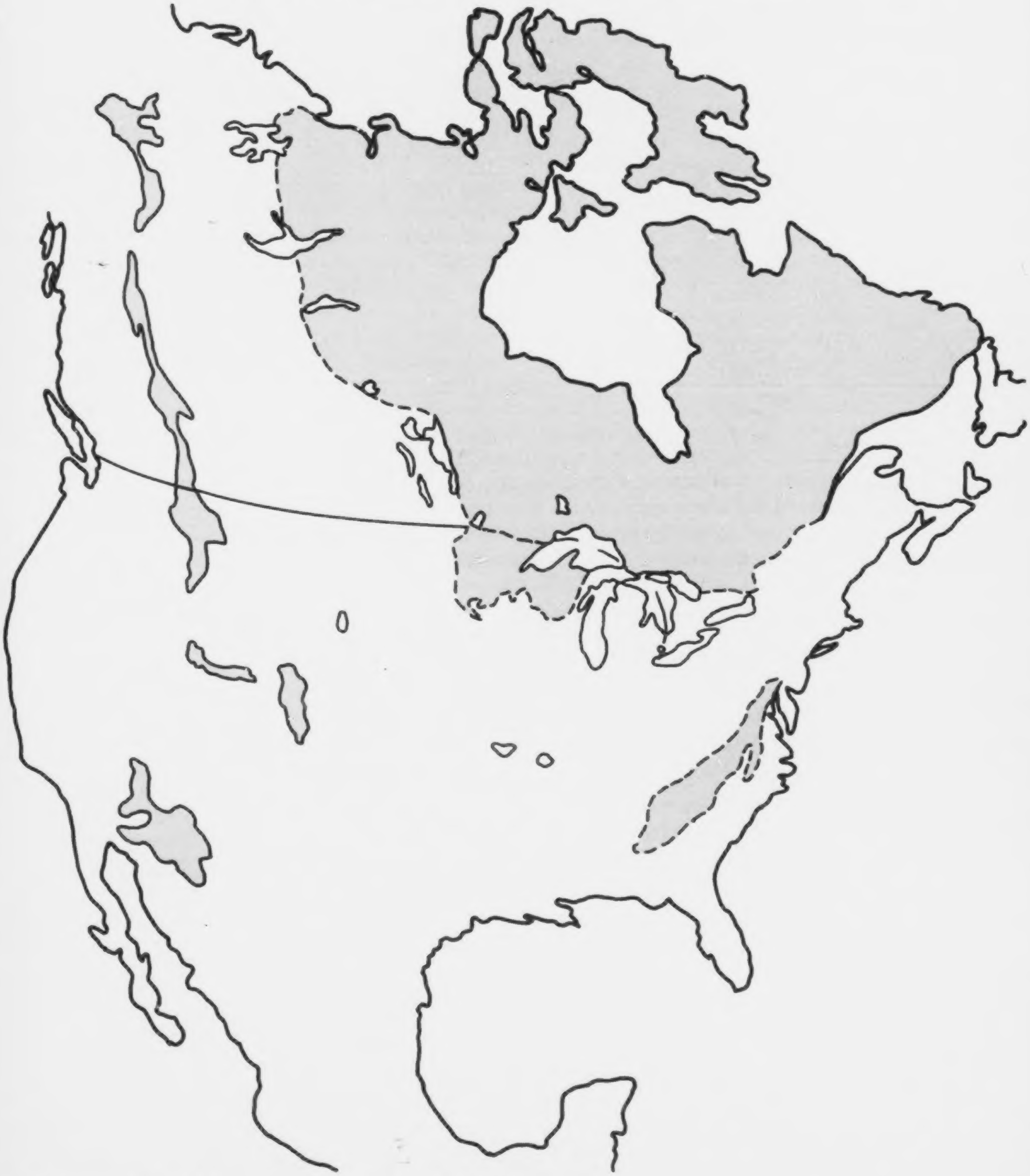
[133] Ibid., p. 11.

[134] Ibid., p. 18.

[135] *Statistical Abstract of the United States*, 1982-83 edition, table No. 1276, p. 715.

Figure 5-9.—Exposure of PreCambrian Rock in North America



SOURCE: Duncan R. Derry, *A Concise World Atlas of Geology and Mineral Deposits*, 1980.

ory. Most currently employed theories of ore genesis are derived from developments in the understanding of plate tectonics and continental drift.[138] These concepts are definitely useful in predicting areas favorable for certain types of mineral deposits and will probably continue to provide practical information.

Advances in this field are expected to call attention to some hitherto ignored, or currently unknown, geologic environments for some metals, particularly gold, silver, and perhaps some base and strategic metals. Explorationists do not feel, however, that any 10-year development of genetic theory will allow them to accurately fix the location and approximate quality of any type of mineral deposit. In fact, there is strong doubt that this could ever be done.

DATA INTERPRETATION

Data interpretation is the single, biggest problem facing exploration. A substantial improvement in this art might far outweigh potential technological improvements.

Both geophysics and geochemistry now can deliver vast amounts of data that no one completely understands. Fully integrating this information with data from other exploration techniques is very difficult. While a very few "seat-of-the-pants" ore finders may be able to do this intuitively, most explorationists are not so gifted. One geologist said, "Better instrumentation is like giving an encyclopedia to an illiterate—the pictures are neat, but it doesn't help him to read."

GEOPHYSICS

Geophysical techniques for locating particular geological structures and compositions are one of the primary screening tools of mineral exploration. The process involves measurement of various physical fields in which variances in mineral content or physical condition will cause anomalies in the data produced.

Current techniques, however, particularly electromagnetic methods, are unable to distinguish between anomalies caused by various minerals such as pyrite, chalcopyrite, or graphite. This prevents the explorer from correctly identifying, or narrowing down sufficiently, the sought-after mineral environment.

Research programs of a few large exploring firms are aimed at developing instrumentation to discriminate between various minerals, particularly sulfides. Because the work is proprietary, very little information is publicly available. Geophysicists interviewed for this report said that such instrumentation would probably not be developed before the end of the century and, even then, may only compound current problems of interpreting findings.

Other than the major problem of data interpretation mentioned above, instrumentation:

- must be better able to screen out natural or human "background noise," this improvement might increase the effective depth penetration, a current limitation of the geophysical techniques; and
- needs additional miniaturization and improvement for borehole use, also increasing depth penetration.

Geophysical techniques are expected to improve only slightly, as many methods are approaching absolute barriers imposed by physical laws. (In particular, the decline of signal strengths by the "inverse of the square of the distance" effect.) Miniaturization of geophysical instrumentation will be much more highly developed. The subsequent increased employment of down-the-hole geophysics will give, in effect, greater depth penetration in areas being explored and could cope with the physical law limits. However, this improvement will be of little use in the initial or reconnaissance stages of exploration.

Geosatellite imagery and other associated data will probably be employed cautiously, but more frequently, particularly if some of the uncertainties of spectral interpretation can be eliminated and higher spectral resolution obtained. Unfortunately, many large, geologically favorable areas of the earth's crust are hidden beneath an alternate environment, preventing satellite identification despite improved technology.

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[138] In 1912 a German, A. Wegener, suggested that about 200 million years ago the continents were packed together in one universal land mass called "Pangaea." Wegener called attention to the "jig-saw" piece matching effect of the South American and African continents; similarities in geology, plant and animal life; and in paleoclimates of various continents. This basic concept received little support until the mid 1950s.

There are no special geophysical problems related to strategic materials that preclude application of general improvements in exploration technology. For example, an effective borehole induced polarization (IP) transmitter and receiver would perhaps be effective in exploration for podiform chromite bodies, in areas where they are known to occur. Cobalt is associated with copper, nickel, and iron sulfides which have detectable electromagnetic signatures. Chromite and manganese oxide can be detected by using certain geophysical techniques as well. However, geophysical techniques have not been developed to identify economic concentrations of metals present in the earth's crust as carbonates and/or silicates (e.g., manganese carbonate deposits and nickel-cobalt silicate minerals in laterites). Limited success has been achieved in distinguishing carbonate and silicate minerals using satellite imagery but only when they appear on the surface. Manganese oxides, as well as sulfides, respond to IP techniques but carbonates offer little, or no geophysical signature. Uncertainties abound, however. IP effects are produced by graphite, magnetite, certain clays, and other minerals. In fact, many IP anomalies have no ascertainable cause.

GEOCHEMISTRY

Geochemistry involves the analysis of soils, surface water, and organisms for abnormal concentrations of minerals. It is one of the basic tools of modern mineral exploration and is relatively rapid, cheap, and direct. But, faster, more accurate, more sensitive, and more specific analytical techniques are needed.

Current practice in sample preparation consists of crushing, grinding, pulverizing, and selecting a sample of appropriate size; each stage of this process offers opportunity for error. The ideal methodology would include automated sample preparation and on-the-spot whole-rock, accurate, multi-element analyses. An instrument for onsite analysis of drill-hole derived samples, at least semiquantitatively, is also needed. A technique that would not alter the physical characteristic of the sample is preferable.

Since strategic materials are not actively explored domestically, accurate multi-element analysis would be highly desirable, no matter what type of sample is being analyzed.[137] Potentially valuable deposits of one element have certainly been overlooked because analytical work was at the time concentrated on locating other elements. Even if no potentially economic element is present, there would be great geologic value in identifying and quantifying all of the trace elements associated with particular types of mineralized bodies. In time, the resulting patterns might offer definite clues to the presence or absence of economic mineralization.

Borehole and handheld instruments, employing X-ray fluorescence analysis methodology, have recently been developed. These are specific for such elements as silver, gold, molybdenum, and tin. But substantial improvements in 6 Compilation procedures for this "unwanted-at-the-time" information would need to be instituted, however, sensitivity and analysis reproducibility are needed. ICP (Inductively Coupled Plasma atomic emission spectrometry) is the latest technique and is claimed to be a multi-element analytical tool. There are, however, substantial problems with inter-element interference and element detection levels.

High-precision and sensitive analytical methods—including ICP, neutron activation, laser bombardment, irradiation by radioactive isotopes—have only limited use in geochemical work because of their high unit costs (more than $50 per sample) and certain physical limitations of the equipment.

The main advances in geochemical exploration are expected to occur in instrumentation and in analytical techniques. Handheld and drill hole-adaptive, direct in situ analytical devices will be available in exploration for some elements, but probably only for PGMs among the strategic metals, since there is little economic interest in the others. Although semiautomated wet chemical analytical methods will be standard, and will increase reproducibility and sensitivity, more highly trained and more costly technicians and analysts will be required to perform the analyses.

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[137] Compilation procedures for this "unwanted-at-the-time" information would need to be instituted, however.

Helicopter-borne spectral reflectance instrumentation, perhaps a spinoff of satellite research, may be used to screen vegetation geochemically in large forested areas. Practical instrumentation should be available that will directly measure gases emitted in decomposition of some economical minerals.

Chromite is a common accessory mineral in mafic/ultramafic rocks, but geochemical surveys have not been successful at identifying economic concentrations of chromite. Widespread high, but very variable, background concentrations of manganese in water, soils, and rocks make geochemical techniques very difficult to employ.

DRILLING TECHNOLOGY

Drilling is the ultimate test phase of all exploration, and its costs, direct and indirect, are one of the most significant limiting factors in minerals exploration today.[138] Improved technology which reduces these costs would allow testing of more targets, however they are identified and defined, and would help improve current ore discovery rates.

Techniques for mineral exploration include core and rotary drilling. Core drilling physically removes a cylindrical sample of rock while a rotary crushes and chips the rock so that only cuttings are removed by air or water.

Core drilling today is not greatly different from that of the 1860s, when it was first employed for coal exploration in Pennsylvania. Although overall technology has steadily improved, only two significant improvements in core drilling have been introduced in the past 30 years. The first was the introduction of wireline drilling (allowing the recovery of a sample core inside a drill stem); the second, the advent of long-wearing, impregnated diamond drill bits.

Rotary drilling techniques for metals have also generally stabilized. Sampling-related problems prevent rotary drilling from being employed to a much greater extent in minerals exploration.

There has been comparatively little direct research directed at improving mineral exploration drilling. The U.S. Bureau of Mines and a drill machine manufacturer and contract drilling company, E.J. Longyear, have jointly designed a method for replacing worn diamond bits without removing drill rods from bore holes, eliminating a costly and time-consuming operation. With the use of impregnated diamond bits, however, it has proven more cost effective to stay in the hole with these longer wearing bits than to purchase the relatively expensive equipment required to change the now partly obsolete surface set bits.

Most incremental improvements in drilling have been developed in oil exploration. Although helpful in strategic materials exploration, various factors—e.g., the size of target, rock types, dimensions of drill holes, and market size differences—prevent large-scale adaptation in mineral exploration. Substantial technical and cost benefits in mineral exploration drilling techniques may be possible only if a long-term, well-conceived, and adequately funded research program is undertaken.

Drilling techniques are not expected to be much different from those employed now. Most explorers foresee increased drilling costs and little change in drilling efficiency. If the rate of growth in average drilling depth is maintained, with its attendant increased costs per hole, it is probable that fewer holes will be drilled on any one target.

Research and Development

Mineral exploration technology and methodology have not been the subject of significant research and development (R&D) attention for some time. Current metal market prices and other problems have led to reductions of previous, modest funding levels in the private sector.

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[138] Dickerson, et al., op. cit., p. 66.

A precise picture of mineral exploration related R&D, however, is difficult to develop. Most work is spread throughout academia (geology), the U.S. Geological Survey (geology, geophysics, and geochemistry), the Bureau of Mines (drilling, geophysics, and miscellaneous pursuits), and mining and oil companies (geology, geophysics, and geochemistry). Equipment manufacturers, with a few exceptions (mainly geophysical contractors), do very little R&D because their markets are so limited.

There appears to be no reliable figure available for the amount of direct exploration-related R&D expenditures for any specific period. (Guesses range from $10 million to $50 million per year by the private sector in North America.) The quantification problem is complicated by no agreed-upon definition of work that should be classified as mineral exploration R&D, especially within the Federal Government. Is a U.S. Geological Survey geologist studying the magnesium content of chromite engaged in mineral exploration research? Most practicing explorationists would say no, but an argument could be made otherwise. One thing is clear to explorationists: R&D in their field, no matter how defined, is, by comparison to most other technical fields, very poorly funded and directed.

Ocean-Based Resources

The floor of the ocean provides a favorable environment for the formation of expansive deposits of minerals containing manganese, iron, and other metals. Some of these deposits contain significant amounts of nickel, copper, or cobalt. As a result, they have gained some attention as possible alternative sources of metals to supplement or replace land-based sources of questioned reliability. The mineral resources of the deep seabed gained visibility during the 1970s when their status was added to many other subjects under consideration at the Third United Nations Conference on the Law of the Sea.

Three forms of the seabed manganese deposits are of interest from a strategic materials perspective: the manganese nodules and crusts located on the Blake Plateau off the coast of Florida, the manganese nodules of the east central Pacific Basin, and the cobalt-rich crusts located on the slopes of seamounts and islands in the Pacific. The status and outlook for exploitation of each of these types of deposits is summarized in table 5-38.

The Blake Plateau deposits contain approximately 15 percent manganese and 15 percent iron, but their content of more valuable metals is low. The water depth ranges between 300 and 1,000 meters, and they are located on the continental slope where they fall under the jurisdiction of the coastal state (in this case, jurisdiction is principally that of the United States, although some of the region is under Bahamian jurisdiction). In 1976, the National Materials Advisory Board evaluated these nodules as a potential domestic source of manganese. The nodules fared well against other domestic sources, but were still judged to be out of the realm of commercial exploitation since their production costs were high in comparison with the large land-based deposits now in production.

The Pacific manganese nodules differ from those of the Blake Plateau in several respects. They have attracted commercial interest because of their content of nickel, copper, and cobalt, which exceed that of many land-based deposits; they are located in water depths as much as 10 times that of the Blake Plateau; and they are located beyond the jurisdiction of any country, with their legal status clouded by the lack of widespread acceptance of any legal regime for exploitation.

Interest in the Pacific nodules began to increase before the technology for exploitation was developed and before the legal regime was developed. The value of the metals contained in the nodules was high in comparison to land-based ores, and the high value of contained metals grabbed attention before estimates of

Table 5-38.—Outlook for Development of Ocean-Based Resources of Strategic Metals

	Blake Plateau	Clarion-Clipperton Nodule Province	Cobalt bearing crusts
Depth	300-1,000 meters	4,000-6,000 meters	1,000-2,000 meters
Location	East coast of Florida, Georgia, South Carolina. Bordered to east by Bahamian jurisdiction	Approximately 1,000 miles southeast of Hawaii. 2,000 miles southwest of California	Continental slopes of Hawaiian Islands, Line islands, and other Pacific seamounts
Metal content:			
Manganese	15.9 ± 7.1%	29.8 ± 20.6%	24.6 ± 4.0%
Iron	15.5 ± 12.5%	14.0 ± 4.8%	14.5 ± 2.5%
Nickel	0.59 ± 0.08%	1.5 ± 0.82%	0.49 ± 0.20%
Copper	0.14 ± 0.4%	1.2 ± 0.49%	0.065 ± 0.39%
Cobalt	0.41 ± 0.35%	0.35 ± 0.12%	0.79 ± 0.33%
Form	Nodules on surface of sediment	Nodules on surface of sediment	Crusts bonded to rock
Status of technology	Limited prototype mining tests completed in 1970	Some prototype mining and processing tests completed in 1980	Limited conceptual proposals for adaptation of nodule mining technology
Economic outlook	Extremely low-grade manganese deposit is not competitive with land-based producers	Low nickel and copper prices make nodule mining subeconomic	Lack of technology, availability of land-based cobalt sources, and uncertain grade and quality of deposits makes economic outlook poor for commercial development
Legal regime	Under U.S. jurisdiction on the Outer Continental Shelf	Beyond U.S. jurisdiction: right to license development activities by U.S. citizens claimed by U.S. but challenged by supporters of the U.N. Convention on the Law of the Sea	Under U.S. jurisdiction on continental slope

SOURCE: Office of Technology Assessment.

the costs of the mining and processing equipment were well developed. It is now apparent that capital and operating costs of deep ocean mining would be much higher that current costs of mining on land, and these high costs more than offset the higher value of the metals that the nodules contain.

There is little detailed information available about cobalt-bearing manganese crusts. These deposits are similar to the Pacific nodules, except that they are in the form of thin crusts bonded to the underlying rock on the slopes of seamounts such as the Hawaiian Islands. In some cases, the crusts have been found to be enriched with cobalt. In some samples, peak cobalt contents of more than 1 percent have been measured, but average cobalt levels have been less than 0.8 percent.

While interest in nodules has declined, the cobalt-bearing manganese crusts of the Pacific seamounts have gained increased attention. The high cobalt content of some of the crusts presents the same attraction that was once presented by Pacific nodules. The high value of the metal contained in the crusts, whether measured in price or strategic interest, overshadows the high cost of recovering the metals from their challenging environment and difficult mineral structure. Even though land-based deposits may have lower content of cobalt, nickel, or copper, they are more attractive to investors because the cost of recovering the metals is significantly lower. For manganese, the case for land-based production is even stronger since land ores are generally higher in manganese content, easier to mine, and more familiar to consumers in the metallurgical industries.

If so desired, the U.S. Government could assist private industry in overcoming the substantial barriers to exploitation of ocean-based resources of strategic materials and thereby encourage industry to commit the major sums needed to build and operate an ocean mine. Unless there is a major increase in prices for nickel, copper, and cobalt, the cost to the government of such assistance would be substantial. Furthermore, an ocean mine would not be secure against interruption; it would be vulnerable to physical interference at sea, and, without a widely accepted legal regime for exploitation of the minerals of the seabed, it could be the subject of international legal and political disputes.

CHAPTER 6

Conservation of Strategic Materials

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CHAPTER 6

Conservation of Strategic Materials

Introduction

Past experience has shown conservation to be an important response to shortages of materials, and strategic materials are no exception. In all of the post-World War II supply disturbances discussed in this report, industry responded with increased recycling and, in some instances, adopted new practices which used materials more efficiently. Conservation also can be an ongoing strategy to reduce industry dependency on insecure sources of supply. In this chapter, several different conservation techniques that can conserve strategic materials are discussed. Included are recycling, product life extension, trimming of alloy additions to the low side of acceptable ranges, and improved processing techniques. Substitute materials and use of surface modification technologies can also conserve strategic materials; these are addressed in chapter 7.

Recycling

Recycling differs from other conservation techniques in that it directly adds to material supplies. Sources of recycled metals include scrap material generated by the primary producer, which is called "home" or "revert" scrap, and secondary (or purchased) scrap. Secondary scrap generated by manufacturers and fabricators is called "prompt industrial scrap," while scrap that comes from products that have been used and discarded is called "obsolete scrap." Another secondary source is process waste that can be reclaimed from metal processing plants.

Purchased scrap (comprised mostly of prompt and obsolete scrap) accounted for 8 percent of domestic cobalt consumption, 15 percent of platinum consumption, and 12 percent of chromium demand in 1982.[1] Actual levels of recycling are significantly higher owing to internal recycling by industry, toll refining arrangements, and incomplete reporting to the Bureau of Mines. In addition, a substantial amount of manganese is recycled from ferrous scrap, and this may grow in the future.

Home scrap, which includes trimmings and ends from castings and overflows from ingots, is generally recycled with great efficiency. Since it is clean and its composition is known, it can simply be returned to the melt for reprocessing.

Recycling of *prompt scrap* is less uniform than home scrap. In large manufacturing operations, where substantial amounts of scrap are generated, efforts to separate scrap by type, to keep it free from contaminants, and to maintain collection and marketing operations are often justified by the market value of the scrap. In smaller operations, or in processes where oils or cutting fluids contaminate the scrap, materials may be discarded as waste. Even when recycling offers economic advantages, firms may not want to divert their resources to the establishment of a new set of internal procedures for segregation and collection of scrap.

Collection of *obsolete scrap* presents even greater problems. This scrap may be disseminated across wide areas and mixed with a variety of other materials. Impurities from metallurgical contaminants must be eliminated to make the scrap reusable. Owing to the expense of collecting, identifying, and separating this scrap, a substantial amount of metal is lost. Even when quantities of known materials are collected, limitations set by the processing technology may result in the scrap being downgraded to a less demanding application. For example, superalloy scrap may be downgraded to make stainless steel in which the cobalt content serves no purpose, and is essentially lost.

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[1] U.S. Department of Interior, Bureau of Mines, *Mineral Commodity Summaries 1983* (Washington, DC: U.S. Government Printing Office, 1982), pp. 32, 36, and 116.

Significant quantities of strategic materials are lost in process wastes, because the costs of treatment or handling for recovery exceeds the value of the contained metals. Technological development, combined with imposition of high costs on the disposal of wastes containing hazardous materials, have given impetus to research on processing of such waste to ease disposal problems and, where possible, to obtain saleable products from the processing.

Advanced Processing and Fabrication Technologies

Industry constantly searches for new processing and manufacturing technologies that can increase production, decrease costs, save energy and materials, or improve performance. Adoption of new technologies sometimes conserves strategic materials. The rapid phase-in of the argon-oxygen-decarburization (AOD) process for making stainless steel during the 1970s is a dramatic case in point. The AOD process led to major improvements in chromium utilization in making stainless steel, including the ability to use more high-carbon ferrochromium (which is cheaper, and requires less energy to make than low-carbon ferrochrome) as a raw material, and enhanced chromium recovery from scrap ferrochromium charges. Nearly all stainless steel producers now use the AOD process, so that further improvements in chromium utilization arising from the process are likely to be modest.

Although it is rare for a new technology to be adopted as pervasively and quickly as the AOD process, ongoing industrial trends in metals processing and fabrication may lead to appreciable savings in some strategic materials on a per-part or per-unit basis in the years to come. For the most part, industry investment in advanced processing and fabrication technologies is driven by concerns about product performance, reducing costs, and minimizing reject parts. Material conservation is not often a primary reason why industry adopts advanced processing technologies, but it is often an important side benefit.

The need for U.S. steelmakers to remain competitive with foreign producers, for example, is leading to the replacement of older, less efficient facilities with new processes which are more cost effective and produce higher quality steel.[2] Furthermore, major savings in manganese can be achieved as steelmakers upgrade basic steelmaking processes. As newer technologies and processes are introduced, important reductions in the amount of manganese needed to process each ton of steel can be expected. The pace of this phase-in will depend on industry resources committed to upgrading of domestic steelmaking capabilities.

Materials conservation is also a side benefit of advanced processing technologies that are increasingly used in producing and fabricating aerospace parts made from superalloys. Often referred to as "near-net-shape" processes, these casting and powder metallurgy techniques are used primarily to reduce costs of machining and to improve control over manufacturing reliability. Because less metal is removed during processing, *product yields* are improved significantly.

Conservation Through Part Life Extension and Design

Life extension approaches to material conservation are of primary relevance to very high-value parts. The overall value of a turbine blade installed in a jet engine, for example, may be 500 times the raw material value. Technologies and maintenance strategies that extend the usable life of a part, therefore, can result in substantial savings in replacement part costs and materials over time.

Some life extension strategies are integrally related to advances in nondestructive evaluation or testing (NDE or NDT) of products. On the inspection line of manufacturing facilities, NDE can be used to identify flawed products which can be immediately set aside for reworking or recycling.

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[2] The need for technological adjustments by the U.S. steel industry is discussed in the OTA assessment, *Technology and Steel Industry Competitiveness*, OTA-M-122, June 1980.

NDE has also been used on the production line to monitor machine tool conditions in order to avoid breakage or other damage. For example, tungsten carbide drill bits have often been retired prematurely because of concern about breakage. A process developed by the National Bureau of Standards for continuous monitoring of the drill bit allows selective retirement of a bit when failure is detected to be imminent, rather than relying on a statistical average or waiting until the bit actually breaks. In addition, since cobalt is used to bind the tungsten carbide, strategic material use may be reduced.

NDE's potential role in monitoring of in-service parts is expected to grow in the years to come as confidence in the reliability of inspection devices increases. Formal retirement for cause maintenance programs are being evaluated by the Department of Defense and may be implemented in the late 1980s.

It is also possible to conserve strategic materials in the design of products. This sometimes happens inadvertently. For example, U.S. automakers, in their effort to downsize cars, have substantially reduced chromium use in cars even though strategic materials conservation was not a primary objective. Design strategies specifically intended to minimize strategic materials use (e.g., industry's effort to conserve cobalt in the late 1970s) are probably rare. However, in many noncritical applications, designers have a wide range of materials that could be used. Actual choice of a material may be governed not only by cost and performance factors, but also by the designers' experience and esthetic considerations. In theory, as computer-aided design technologies and computer-aided selection of materials advance, designers may become more aware of alternative materials that use less strategic materials.

Design of products so that they can be easily recycled is another frequently proposed conservation technique. However, the trend in some industries is toward use of more complex materials and products that pose greater difficulties for recycling.

Interrelationships of Conservation Approaches

As discussed in subsequent sections of this chapter, the prospects for conserving strategic materials in many applications are quite good. However, the extent to which any given approach will be adopted by industry will depend on how well it fits into the overall corporate strategies of many different firms. Generally speaking, strategic materials conservation per se is seldom a primary motive in industry decisions—although it is sometimes an ancillary benefit.

In the future, industry concerns about competitiveness, improving product performance, and cutting production costs will lead to adoption of new technologies, some of which may lead to conservation of strategic materials. It is difficult, however, to predict overall impacts of conservation on U.S. import reliance: these new technologies will interact in complex ways—sometimes simultaneously in a given application. For example, increased use of materials-efficient fabrication processes in the aerospace industry will reduce the amount of home and prompt superalloy scrap that would otherwise be available for recycling. The overall effect of this on strategic materials use, however, is likely to be positive, since some fabrication scrap is difficult to recycle. Life extension techniques would reduce demand for replacement parts containing strategic materials, but would also reduce the quantity of obsolete scrap available for recycling.

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Case Studies of Strategic Materials Conservation Opportunities

Conservation of some strategic materials increased during the late 1970s and early 1980s, encouraged in part by higher costs for raw materials and energy, Government waste disposal requirements, and industry investment in new materials-efficient technology. However, major opportunities to conserve strategic materials are still evident. These vary by material and application:

1. Despite advances in manufacturing technologies, total cobalt losses in 1980 in unrecovered or downgraded scrap, or in processing wastes, amounted to 7.7 million pounds—nearly half of the estimated 16.5 million pounds of cobalt actually consumed domestically that year.[3] By far, the largest opportunity for increased cobalt recycling lies in the increased recovery of obsolete scrap. Of the 6.3 million pounds of cobalt in products estimated to have become obsolete in 1980, nearly three-fourths (about 4.6 million pounds) was unrecovered or downgraded. Potential sources for improved recovery include superalloys from obsolete jet engine parts and cobalt-bearing catalysts. Other cobalt recycling opportunities include reduction of downgrading of obsolete scrap and improved recovery of processing waste, which together entail cobalt losses of 3.1 million pounds.

2. The steel industry is the country's dominant user of manganese, consuming nearly 90 percent of total U.S. requirements. Manganese consumption is dependent not only on the amount of steel produced, but also on how efficiently manganese is used in steel production. Significant future reductions in the amount of manganese needed per ton of steel are expected: greater attention to trimming is expected to reduce the average amount of manganese in steel by 12 percent, from 13.8 to 12.2 pounds per ton by 2000. This, together with adoption of improved steelmaking technologies, such as external desulfurization, continuous casting, and ladle and secondary refining techniques are likely to decrease the amount of manganese required to produce a ton of steel from 35.6 to 24.8 pounds by the year 2000. The consumption of imported manganese ore and ferromanganese is estimated to decline from 17.8 pound per ton of steel to 9.5 pound per ton, a reduction of over 45 percent. Most of these technologies will be implemented for product quality and cost competitiveness reasons.

3. Widespread adoption of the AOD process by stainless steelmakers led to industrywide improvements in chromium use that are not likely to be repeated soon. However, chromium conservation opportunities, including increased recycling, and reduced overspecification of materials, could lead to major savings. In the 1977-81 period, an average of 64,000 tons of chromium contained in purchased stainless steel scrap was recycled each year.[4] By contrast, an estimated 62,000 tons of chromium contained in obsolete stainless steel scrap went unrecovered or was downgraded in 1977 (the last year for which detailed estimates have been made). The largest single opportunity for enhanced recovery of obsolete scrap is in automotive recycling, where most chromium-bearing scrap is downgraded. Chromium recovery from industrial processing wastes is increasing, owing to adoption of collection procedures and commercial reprocessing systems.

4. The high price of platinum group metals (PGMs) encourages highly efficient use of these materials. Recycling probably accounts for over 40 percent of U.S. PGM consumption when internal (toll refining) recycling by industry is taken into account. The key opportunity for increased recycling over the next 10 to 15 years will be recovery of PGMs from automotive catalytic converters which could add up to 500,000 troy ounces annually to U.S. PGM

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[3] National Materials Advisory Board, *Cobalt Conservation Through Technological Alternatives*, publication NMAB-406 (Washington, DC: National Academy Press, 1983), fig. 3 (p. 23) and table 11 (p. 24).

[4] U.S. Department of Commerce, *Critical Materials Requirements of the U.S. Steel Industry* (Washington, DC: U.S. Government Printing Office, 1983), p. 62.

supplies by 1995. Obsolete electronic scrap is also a promising source for secondary recovery of PGMs, even though such scrap is disseminated widely throughout electronic equipment which, in turn, is spead all across the country, making collection and separation of metals expensive. The Department of Defense, which is a large generator of electronic scrap, and the Bureau of Mines, have cooperated in developing improved means for processing this scrap.

In the pages that follow, prospects for strategic materials conservation in certain specific applications are discussed.

Superalloys

Superalloys constitute the largest single category of cobalt use. They are also the principal users of high-purity chromium metal and major users of low-carbon ferrochrome. Typical cobalt-base superalloys contain up to 65 percent cobalt- and nickel-base, alloys may contain up to 20 percent cobalt. Chromium content ranges between 10 and 25 percent.

Since 1978, when disturbances in Zaire led to widespread concern about cobalt supplies, manufacturers of aircraft jet engines and engine components and several Federal agencies have placed increased emphasis on reducing the need for cobalt in jet engines. One approach, covered in detail in chapter 7, is the development and use of substitute alloys that contain less cobalt. Other approaches emphasize conservation, through recycling of superalloy scrap, use of near-net-shape manufacturing processes to reduce fabrication scrap, and extension of the useful life of components. As industry adopts these techniques, the need for cobalt, and for other strategic metals, such as chromium, nickel, and tantalum, will be reduced on a per part basis.

Substantial amounts of cobalt, chromium, and other strategic metals used in the production and fabrication of superalloys do not end up in the final part. Table 6-1, adapted from a 1983 National Materials Advisory Board (NMAB) report on cobalt conservation opportunities,[5] estimates sources and end results of the cobalt used in the production of superalloys in 1980, the most recent year for which detailed information is available. Several important points can be drawn from the table:

Table 6-1.—Cobalt Consumption in Superalloys, 1980

	Wrought	Cast	Total
Input:			
Primary cobalt	3.47	1.73	5.20
Prompt scrap	0.26	1.50	1.76
Obsolete scrap	0.87	0.32	1.19
Total production	4.60	3.55	8.15
Output:			
Final parts	2.34	1.24	3.58
Total lost	2.00	0.82	2.82
(Waste)	0.21	0.28	0.49)
(Downgraded)	1.79	0.54	2.33)
Prompt scrap	0.26	1.50	1.76

SOURCE: Adapted from National Materials Advisory Board, *Cobalt Conservation Through Technological Alternatives*, National Academy of Sciences, 1983, pp. 147, 148.

- Of nearly 8.2 million pounds of cobalt used in superalloys in 1980, only 3.6 million pounds, less than 45 percent, were contained in final parts.
- Almost 55 percent of the consumption of *primary* metal was lost through downgrading or waste in the production of superalloy parts in 1980.
- Almost 44 percent of the initial amount of wrought alloys were lost or downgraded; for cast alloys the fraction is lower, about 23 percent.
- The use of obsolete superalloy scrap was quite low, accounting for less than 15 percent of the total cobalt used in processing superalloys. NMAB also estimated that only half of the cobalt in superalloy scrap that became obsolete in 1980 was recovered for recycling by the superalloy industry (1.19 million out of 2.4 million pounds).

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[5] *Cobalt Conservation Through Technological Alternatives*, op. cit. Some uncertainty surrounds the estimates shown in table 6-1, owing to the inadequacy of the available data on scrap use and new cobalt requirements of the superalloy industry. As a result, various assumptions had to be employed by NMAB to approximate conditions in 1980. While NMAB believed its cobalt material flow model to be "reasonable approximation of reality," it noted that further work would be needed to confirm or reject its assumptions (pp. 25-26).

These statistics suggest the tremendous potential of conservation techniques to reduce requirements for primary cobalt. In 1980, 2.8 million pounds of cobalt were lost through downgrading and to waste in fabrication of superalloy parts. In the future, much more of this material may be recoverable as superalloy recycling technologies advance. Alternatively, the amount of material lost could also be reduced through the increased use of near-net-shape manufacturing processes, particularly with respect to the wrought alloys.

Obsolete scrap is a large potential source of cobalt. Most of the 3.58 million pounds of cobalt used in finished superalloy parts in 1980 will eventually be available for recycling, but much of this material may be downgraded unless jet engine manufacturers are confident that scrap can be safely recycled for jet engines. The raw materials for superalloys, whether it is cobalt, nickel, chromium, or ferrochromium, must be of the highest purity in order to avoid faults in the final part that could cause it to fail. Thus, manufacturers of aircraft engines often prohibit use of obsolete scrap unless certified processes for collecting and processing the scrap have been approved. Rates of obsolete scrap generation in the future may be affected by techniques that extend the service life of parts.

Near-Net-Shape Processes

The use of high-temperature alloys in a jet engine is very inefficient in terms of the amount of material consumed to produce a finished part. Ratios of 8 to 1 for input material to final part (also referred to as the "buy-to-fly" ratio) are common, and ratios of 20 to 1 are not unheard of. This ratio can be significantly reduced by near-net-shape processes.[6] Three general types of near-net-shape processes are in use at this time: precision casting, advanced forging, and powder processing.

PRECISION CASTING

Casting, the solidification of molten metal in molds, is a near-net-shape process that has been used for jet engine components since the birth of the industry. Casting is very efficient in its use of material. Although it is necessary to use gates and risers to control the flow of metal into the mold, resulting in as little as 40 percent of the metal actually ending in the final casting, large castings are very near to their final shape (only 5 to 10 percent of the material needs to be removed during the final machining and finishing operations). Further, most of the scrap generated in casting is "immediate revert"—that is, it can be recycled without further processing. Since it is recycled in the same shop in which it is generated, segregation and identification are simple matters. Therefore, most material poured from the melting furnace is eventually used.

Recent trends in casting technology have resulted in precision castings of up to 500 pounds (typically 10-pound units were produced in the past). This results in two advantages. First, a larger portion of the engine can be produced by the material-efficient casting method, and second, the elimination of numerous steps of component assembly reduce the cost of assembling the engine.

New casting technologies have also resulted in improved material properties. Through the use of directional solidification, components, principally blades and vanes, can be cast so that grain boundaries are very long and are aligned with the axis of the component. It is also possible to cast components as a single crystal, eliminating grain boundaries altogether. This allows the elimination of elements that are often added to strengthen grain boundaries, such as zirconium and hafnium.

ADVANCED FORGING METHODS

Closed die forging is used extensively to fabricate gas turbine components ranging from small turbine buckets to large fan blades and very large disks. In this process, the starting stock is heated to various temperatures depending on the alloy being forged and is placed between two dies that are forced together, enclosing the stock and deforming it to the shape of the die. Usually the starting stock is wrought—i.e., it consists of a bar or billet that has been hot-worked from an ingot. The hot working ensures that the original casting achieves full density and chemical homogeneity.

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[6] These processes are discussed in detail in *New Metals Processing Technologies*, a report prepared for OTA by Charles River Associates, Inc.

The major disadvantage of this process, as conventionally practiced, is that a large amount of the material must be removed to reach final shape. It is common for the final part to contain only one-tenth of the original materials. This large material loss due to forging may be considerably reduced through the use of two advanced technologies.

Isothermal Forging.—Isothermal forging is distingushed from conventional forging operations in that the temperature of the forging die is the same as the piece being worked, approximately 1,750° to 1,950° F. Through reduction of heat loss from stock to die, the plastic deformation of metal is significantly improved. The operation is conducted in an inert gas atmosphere. Parts can be processed to close to the final specifications, although the shape must be configured to allow nondestructive inspection, usually by acoustic methods (hence the term "sonic shape" for the form as it leaves the die). Further machining is required to reduce the shape to its final dimensions. Pratt & Whitney Aircraft has patented and licensed a variation of the isothermal forging process which it claims can reduce the input material by 50 percent, thereby making a large reduction in the "buy-to-fly" ratio. Isothermal forging is now routinely used for the forging of turbine disks. bine disks.

Near-Isothermal Forging.—Also referred to as "hot-die forging," near-isothermal forging differs from isothermal forging in that the die is not heated to the temperature of the stock, but to 150° to 300° F below the stock temperature. The operation is conducted in air and can be adapted to conventional presses, making it more widely available at a lower cost than isothermal forging. Although the improvements are not as great as those for isothermal forging, this process does reduce the amount of input material required by conventional closed die forging.

POWDER PROCESSING

A third process for the manufacture of superalloy components is based on the processing of ultrafine powder into billets or parts. The powder may be of a single composition or a mixture of materials. By the latter method, oxide dispersion-strengthened alloys, such as MA-754, are produced.

Powder metallurgy is attractive, not just because it can produce new materials, but because it can produce substantial reductions in the amount of scrap generated during forming operations. Powder "pre-forms" are produced by techniques similar to casting processes. The pre-forms are then compressed at high temperatures and pressures to eliminate voids and inclusions. The components are then ready for inspection and final machining.

The combination of powder pre-forms and hot isothermal forging has allowed the development and use of some of the most advanced nickel-based alloys in turbine disks, including IN-100, MERL-76, and Rene-95, none of which could be reliably formed into components by conventional means.

The advantages of powder metallurgy are not limited to conservation of strategic metals in the more exotic applications such as jet engine components. Gears and camshafts, parts which normally require considerable machining, can be manufactured to near-net shape by powder pre-forms, thereby reducing scrap production and machining. The need for resulfurized steel in these applications, normally used for its improved machining characteristics, can be eliminated as well, reducing the requirements for manganese in this type of steel.

Recycling

Until cobalt supplies were seen as threatened by the 1978 Katangese rebellion in Zaire, recycling in the superalloy industry was largely limited to home scrap. Prompt industrial scrap and obsolete scrap were either downgraded for stainless steel production or exported out of the country. As prices rose and supplies became uncertain, the importance of recycling of superalloy scrap became apparent. Alloy producers, parts fabricators, and turbine manufacturers began to segregate fabrication (prompt industrial) scrap by alloy type so that it could be remelted and reused. Some turbine manufacturers modified earlier specifications to allow greater use of prompt industrial scrap and even some obsolete scrap, provided that the source and type of the scrap was known. The exact amount of the savings provided by recycling during the period of high cobalt prices ($25 per pound at their producer price high point in 1979-80) is not known, but domestic consumption of primary cobalt in superalloys was probably 10 to 25 percent less than might otherwise have been the case.[7]

Identification and separation of scrap is time consuming and expensive. With 1983-84 cobalt prices ranging from $6 to $12 per pound, it is not clear whether the gains made in the late 1970s will continue. Some firms have continued their recycling programs, particularly for prompt scrap, by encouraging suppliers and customers to separate scrap by alloy type. Specialized scrap processing firms now have greater experience with this kind of recycling, which may encourage jet engine manufacturers to update specifications to allow greater use of scrap in the production of superalloys. Once such specifications are established, recycling of superalloy scrap can be increased quickly in response to increased metal prices or supply uncertainties.

PROCESSING OF SUPERALLOY SCRAP

Commercially used technologies for recycling superalloy scrap are based on the same processes used in the original production and refining of the alloy, including vacuum induction melting and vacuum arc remelting, but strict attention is paid to segregation of scrap by type.

For production of superalloys, uncontaminated home scrap of known composition can be and is reverted directly to the charge. Additional processing sometimes involving several steps may be needed if prompt industrial scrap or obsolete scrap is to be recycled.

Vacuum and air furnace technologies needed to remelt high-quality superalloy scrap into usable master alloys are already in place in the United States. In-house scrap is now carefully separated and routinely added to the alloy melt by many producers of superalloys, and a specialized industry has developed to produce master alloys from fabrication scrap. Some firms report that they now recover virtually all in-house scrap. Obsolete scrap is also recycled to some extent, although generally not for the most demanding application—rotating parts of jet engines. As is discussed in box 6-A, instruments able to identify complex alloys and contaminants are now being marketed and may alleviate some technical problems associated with scrap sorting. According to recycling industry sources, several million pounds of high-temperature alloy scrap have been shipped from scrap processors to melters in the last 10 years.[8]

Air-melting processes, involving electric furnace melting of the scrap charge and subsequent refining in an argon-oxygen-decarburization vessel, can produce alloys from scrap that are suitable for many noncritical superalloy and super stainless steel applications, but are not appropriate in critical applications such as gas turbines used in aviation. Nickel and cobalt recovery is high, but readily oxidizable alloys are lost in the slag. Air melting of scrap can also be used to produce master melt alloys suitable for further processing through vacuum melting into superalloys.[9]

Vacuum melting processes are used to produce superalloys suitable for the most demanding applications or superalloys containing highly reactive elements. Only the highest qual-

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[7] As discussed in Charles River Associates, Inc., *Effects of the 1978 Katangese Rebellion on the World Cobalt Market*, contract report prepared for OTA, December 1982, pp. 1-6.

[8] Information provided by the National Association of Recycling Industries.

[9] J. J. deBarbadillo, "Nickel-Base Superalloys: Physical Metallurgy of Recycling," *Metallurgical Transactions A.*, vol. 14A, March 1983, p. 332.

Box 6-A.—Scrap Sorting and Identification Instruments

Recycling of complex materials requires detailed knowledge of scrap constituents. Nickel- or cobalt-based superalloy scrap may contain 8 or even 10 separate alloying elements, as well as potentially troublesome tramp elements and contaminants that need to be removed during processing. Concerns about scrap quality are not limited to superalloys: in stainless steel production, for example, presence of phosphorus in scrap needs close monitoring, due to its adverse effect on working, forming, and ductility of stainless steel. Very small amounts of titanium in scrap charges are believed to be harmful in tool steels and high strength steels. Failure to correctly identify and sort scrap is a major reason for the extensive downgrading of superalloy and stainless steel scrap that is still prevalent.

Certification requirements placed on scrap processors by their customers have become increasingly stringent. In some premium uses, scrap processors may have to identify scrap constituents to an accuracy of a few parts per million. Under these circumtances, conventional scrap sorting techniques—entailing visual inspection, magnetic separation, or spark testing—are not sufficient in themselves.

Growth in recycling of superalloys and specialty materials during the last decade has led to increased use of mobile and inexpensive ($4,000 to $50,000) sorting instruments. These devices were not developed primarily for use in scrap processing, but most can be used by unskilled operators (or in some cases trained technicians) to identify complex scrap components more accurately.[16] Some of these (e.g., chemical spot testing) are used to confirm the presence of alloys after preliminary hand sorting is carried out. These techniques are qualitative or semiquantitative in nature. More complex readings can be obtained through X-ray spectrometers, thermoelectric instruments and eddy current devices—all of which are now available as portable units which can be used in scrap yards.[17]

A recent recycling advance has been linkage of scrap identification devices to user friendly computers, which provide workers with step-by-step procedures for classifying scraps. Commercially available programs specifically geared to the needs of small firms in the recycling industry have been marketed for several years. One such program, used in conjunction with a portable X-ray spectrometer device, reportedly allows rapid identification of up to 16 elements in a sample.[18] Initial analysis can be completed in 10 to 50 seconds; a more complete quantitative analysis requires several minutes, if needed. If properly programmed, the computer will identify the trade name of the alloy or materials which the scrap most closely approximates. This is especially useful in obsolete scrap identification, where the origin of the materials may not be known.

Identification devices are increasingly used by the scrap industry—with the encouragement of the National Association of Recycling Industries, the Institute of Scrap Iron and Steel, and the Bureau of Mines. Most of these instruments were designed for laboratory or scientific use, not the difficult operating environment of the scrap yard. Portable devices have the ability to test a large number of samples rapidly on site, but are not capable of such detailed analysis as laboratory or stationary instruments. As instrument manufacturers become more aware of the scrap industry, instruments specifically designed for scrap industry use may be developed.

Likely trends in materials processing suggest that scrap classification techniques will need continuing refinement. Use of more complex alloys, and parts made from multiple alloys will increase recycling difficulties.

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[16] Xavier Spiegel and E. Horowitz, *Instruments for the Sorting and Identification of Scrap Metal*, Sponsored by the Institute of Scrap Iron and Steel (Baltimore, MD: The Johns Hopkins University Center for Materials Research, Oct. 15, 1981), p. 1.

[17] Newell, R. E. Brown, D. M. Soboroff, and H. V. Makar, *A Review of Methods for Identifying Scrap Metals*, Bureau of Mines Information Circular 8902 (Washington, DC: U.S. Government Printing Office, 1982).

[18] As discussed in: "Philips PB9500 X-RaySpectrometer Speeds Recycling of Critical Materials," *Norelco Reporter*, vol. 28, No.1, May 1981, pp. 40-42.

The Bureau of Mines is identifying alloys for which current identification and sorting methods are not adequate, as a preliminary step towards development of new methods.[19] Another area of government R&D (undertaken by both the Bureau of Mines and the National Bureau of Standards) is instrumented spark testing techniques, which could reduce subjectivity in spark analysis by workers.

Ultimately, effective recycling requires well-developed linkages among processors, melt shops, fabricators, and manufacturers. During the last decade, many firms in the superalloy industry established recycling programs, entailing close coordination of requirements along the entire chain of the industry. A properly controlled program to ensure scrap integrity entails accurate separation and identification of scrap, and adequate measures to reduce risk of contamination.[20]

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[19] U.S. Department of the Interior, Bureau of Mines, *Avondale Research Center Research Program Fiscal Year 1983*, (n.p., n.d.)

[20] A detailed discussion of superalloy scrap processing requirements can be found in R. S. Cremisio and L. M. Wasserman, "Superalloy Scrap Processing and Trace Element Consideration," *Vacuum Metallurgy: Proceedings of the 1977 Vacuum Metallurgy Conference*, R. S. Krutenat (ed.) (Princeton, NJ: Science Press, 1977), pp. 353-388.

INCONEL 625

Photo credit: U.S. Department of the Interior, Bureau of Mines

The first step in recycling strategic metals in superalloys is accurate identification of the alloy itself. In this Bureau of Mines procedure, sparks generated by touching an alloy sample to a grinding wheel are analyzed spectrographically, and the spectrographic "fingerprint" is identified by a computer

ity of scrap is suitable for vacuum melting. Such scraps are certified by alloy content and must be free of contaminants and tramp elements. With careful separation and identification, some in-house scrap and fabrication scrap of known composition and history can be vacuum melted without extensive preprocessing.

In the long term, the potential for recycling will depend more heavily on obsolete scrap as the use of near-net-shape technologies increases. Where traditional machining of superalloy parts can typically require up to 10 times as much material as contained in the final part, new processes can reduce this figure to as low as 2 or 3 to 1. This reduces the amount of prompt scrap generated and thus increases the importance of obsolete scrap.

The technical feasibility of using obsolete superalloy scrap to produce investment cast jet engine turbine blades has been demonstrated by Certified Alloy Products. The company reportedly has produced a master alloy from used superalloy turbine blades.[10] The process entails oxygen lancing in an electric arc furnace, followed by refining in a vacuum induction furnace. Testing of blades made from the recycled alloy showed comparable quality to turbine blades manufactured from virgin materials. The firm developed the process in the aftermath of the 1978 cobalt price spike and has subsequently discontinued its use.[11] Although such techniques may enhance the potential for reuse of obsolete superalloy scrap, further work to establish process reproducibility and results may be needed.

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[10] This process is described in Michael J. Woulds, "Recycling of Engine Serviced Superalloys," *Superalloys 1980: Proceedings of the Fourth International Symposium on Superalloys*, John K. Tien, et al. (eds.) (Metals Park, OH: American Society for Metals, 1980), pp. 31-41.

[11] Private communication between personnel of Certified Alloy Products and OTA staff in May 1983.

Both vacuum and air melting furnace technologies continue to evolve. New processes, such as Electron-Beam Refining, Vacuum Arc Double Electrode Remelting (VADER), and Plasma Arc processes may have considerable relevance to superalloy recycling. Some of these technologies are in the early stages of use in the United States.

Several laboratory-scale processes have been developed which separate superalloy scrap into its constituent metals, but none have been commercialized. Such techniques overcome most concerns about contaminants. In a laboratory project sponsored by the U.S. Bureau of Mines, Inco developed a process that utilized a combination of hydro- and pyro-metallurgical processes to recover 93 percent of the chromium, 99 percent of the nickel, 96 percent of the cobalt, and 92 percent of the molybdenum from clean, solid superalloy scrap.[12] Other Bureau of Mines research projects on superalloy scrap are underway. In one experiment, the superalloy scrap is melted with aluminum or zinc to form an intermetallic compound which can be crushed into small particles. The particles are then dissolved by acid; the resulting solution would then be treated hydrometallurgically to recover the metals. The process is thought to be especially promising as a means for recycling mixed combinations of bulk superalloy scrap which have not been sorted.[13]

GTE Sylvania Corp. has a commercial facility for recovering high-purity cobalt from secondary sources that include some types of superalloy scrap, including grindings. GTE's proprietary manufacturing process uses chemical means to recover highly purified cobalt powder that is now used in cemented carbide products. The firm is considering a larger scale recovery process which would produce compacted briquettes of cobalt that may be suitable for superalloy production.[14]

Commercialization of advanced superalloy reclamation processes by industry is impeded by the currently low price of cobalt. Plans to undertake a pilot plant to test the Inco/Bureau of Mines laboratory process discussed above were discontinued when cobalt prices fell in the early 1980s. Feasibility studies showed that the pilot plant process, and a small-scale commercial facility would have been profitable at 1980 metal prices, but would operate at a deficit at cobalt prices in the 1981-84 period. Estimated costs of a pilot plant project able to handle 100 pounds of scrap feed per hour were estimated to be about $5 million in 1980 dollars, assuming no donation of equipment by industry. Operating costs for such a facility would be in the neighborhood of $2 million for an 18-month period.[15]

RETIREMENT FOR CAUSE AND PRODUCT LIFE EXTENSION PROGRAMS

Currently, critical components of jet engines, such as turbine disks, are retired from service on a predetermined schedule, based on the number of hours a part has been in operation—not on the basis of actual detection of flaws or defects in the part. This has been necessary because of difficulties in detecting the early stages of flaws that could lead to a disastrous failure of a part. While the current retirement procedures minimize risk of failure, most parts are removed from service long before actual flaws occur.

Turbine disks used in the F-100 jet engine, for example, are only kept in service for the number of hours in which there is a statistical probability of a fatigue crack developing in one out of a thousand disks. As a result, 999 parts can be expected to be removed from service prematurely for every single part that is defective. Subsequent testing has shown that the useful life of many of these retired parts could be 10 times longer than the disk in which the initial crack occurs.[21]

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[12] J. J. de Barbadillo, J. K. Pargetter, and H. V. Makar, *Process for Recovering Chromium and Other Metals From Superalloy Scrap*, U.S. Department of the Interior, Bureau of Mines Report of Investigation 8570 (Washington, DC: U.S. Government Printing Office, 1981).

[13] Jerald R. Pederson, compiler, *Bureau of Mines Research 1983* (Washington, DC: U.S. Government Printing Office, n.d.), p. 103; and G. B. Atkinson, *Increasing the Leaching Rate of Bulk Superalloy Scrap by Melting With Aluminum*, U.S. Department of the Interior, Bureau of Mines Report of Investigations 8833 (Washington, DC: U.S. Government Printing Office, 1983).

[14] Information provided by GTE Products Corp.

[15] Information provided by the U.S. Bureau of Mines.

With the substantial technical advances that have been made in NDE in recent years, it may soon be possible to evaluate individual parts from operating jet engines at prescribed intervals in order to determine whether the initial stages of a flaw have appeared. Parts which have such flaws could then be retired for cause (RFC); those without flaws could be kept in service.

Such a strategy underlies the Air Force's Wright-Patterson Aeronautical Laboratory evaluation of methodologies for a maintenance program based on retirement for cause. If implemented, the program will permit parts from some jet engines to be used until there is actual evidence of an incipient flaw. An actual decision about implementing the program will probably not be made until after 1985. However, early indications are that the program has the potential to reduce spare-part requirements, and therefore to conserve strategic materials.

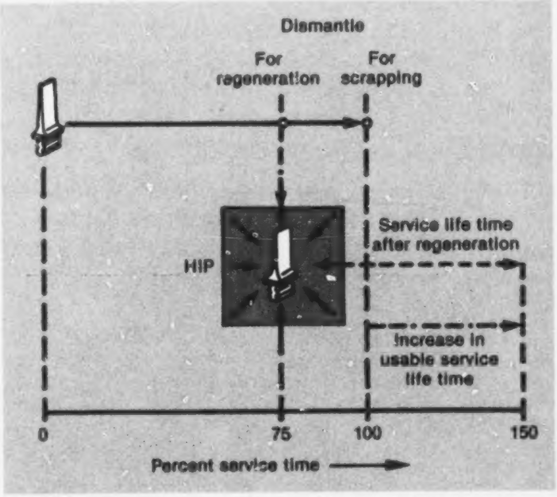
The initial Air Force evaluation centers on the F-100 jet engine. If initiated in 1985, the program's savings in spare parts over the 15-year average engine service life left in the F-100 fleet could be $249 million. By 2000, a 70 percent material savings from requirements for reduced spare parts would also be achieved, according to the Air Force.

A related Air Force initiative is aimed at "stockpiling" retired jet engine parts until they can be returned to service rather than simply disposing of them as scrap, as is ordinarily done.[22] Many of these parts have been retired simply because they have reached the end of the predetermined service life discussed above, and could be returned to service if retirement-for-cause (RFC) methodologies are implemented. These parts are also being used as test specimens for the evaluation of RFC methodologies. Other parts in these "holding accounts" may be capable of rejuvenation through current and prospective technologies discussed in the previous section.

It is possible to extend the lifetime of components of the jet engine if flaws and defects can be caught at an early time. Researchers in West Germany, for example, have reported that if an engine is dismantled at three-quarters of its normal life and the turbine blades are subjected to hot isostatic pressing to eliminate incipient cracks, the overall life of the blades will extend to 50 percent beyond their normal life in service, as illustrated in figure 6-1.

Hot isostatic pressing (HIP) has also been shown to extend the service life of vanes and blades if it is used as a post-casting treatment to eliminate all porosity remaining in the material after casting. The post-casting HIP treatment has been shown to increase the average stress-rupture life by 100 percent and the fatigue life by 800 percent in two nickel-base alloys, B-1900 and IN-792, both modified by the addition of hafnium.

Figure 6-1.—Service Life Time of Turbine Blades


Dismantle
For regeneration
For scrapping
HIP
Service life time after regeneration
Increase in usable service life time
0
75
100
150
Percent service time

SOURCE: H. Huff, R. Gräter, and R. Fröhling, "Measures for Materials Conservation in Aero-Engine Construction," paper delivered to the NATO Advisory Group for Aerospace Research and Development Conference, Vimeiro, Portugal, October 1983.

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[21] J. A. Harris, et al., *Concept Definition: Retirement for Cause of F100 Rotor Components*. Technical Report AFWALTR804118 prepared for U.S. Air Force Materials Laboratory at Wright-Patterson Air Force Base by Pratt & Whitney Aircraft Group (Washington, DC: U.S. Government Printng Office, 1981).

[22] Information provided by the U.S. Air Force.

A quite different approach toward material conservation is to design parts for the life of the aircraft. Such approaches may require more strategic materials to be used in the initial part, but because these parts have a longer life expectancy, the end result may be to conserve materials. Such strategies are being evaluated through the engine structural integrity program of the Air Force.

OUTLOOK FOR CONSERVATION OF STRATEGIC MATERIALS IN SUPERALLOYS

All of the factors discussed above—materials-efficient processing, recycling, and life extension—will play a role in determining conservation levels achievable in superalloy production and parts manufacturing. More efficient processing and fabrication could reduce input raw materials needed for each jet engine by 10 percent by 1990 and 25 percent in the early years of the next century, compared to current levels. This is a judgmental estimate, which assumes that many currently used technologies (which are less efficient in conserving materials) will continue to be used throughout much of the period. Advanced technologies are likely to be introduced primarily when new alloys and successive generations of jet engines are brought into production, typically at 5- to 10-year intervals.

As fabrication becomes more efficient, home and prompt scrap—now preferred for recycling—will comprise a less important portion of the materials available for recycling. If processing problems are overcome, obsolete scrap will probably ascend in importance, although to what extent is difficult to foresee. Part life extension technologies and RFC maintenance philosophies could extend the material life cycle, thus temporarily reducing obsolete scrap production levels, even if advanced recycling technologies are implemented.

Development of new alloys and manufacturing techniques by superalloy producers and jet engine makers can have unpredictable effects on recycling. Increased use of powder metallurgy, coatings, multiple alloy components, and phase-in of advanced ceramics and composites may make the job of recycling more difficult. For example, coated or clad superalloys may reduce the value of some superalloy scrap owing to added costs of identifying and recovering the surface layer. Continuing evolution in scrap processing technologies to keep pace with rapid changes by producers and component manufacturers will be required if the promise of recycling is to be realized.

Conservation of Manganese in the Steel Industry[23]

Nearly 90 percent of the manganese consumed in the United States is used in the production of steel, either as an alloying element or as a processing agent.[24] Consumption of manganese in this industry is dependent not only on the level of steel production, but also on the mix of steel grades produced and processing technologies used. This section discusses the function of manganese in both steel and steelmaking, and assesses the effects of product and processing trends on the pattern of manganese use in the steel industry.

Manganese as an Alloying Element in Steel

Manganese is second only to carbon in importance as an alloying element in steel. Through its influence on steel chemistry and microstructure, manganese influences an assortment of physical and mechanical properties. As discussed in box 6-B, manganese provides sulfur control, enhances hardenability, wear resistance, and solid solution strengthening, and retards recrystallization. The amount of manganese used as an alloying element depends on the specific property requirements of the particular steel product. Some grades make greater use of it than do others.

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[23] Much of the analysis in this section was based on G. R. St. Pierre, et al., *Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an Alloying Element in Steels*, OTA contractor report, February 1983.

[24] Based on data from *Minerals Yearbook Volume I* (Washington, DC: U.S. Bureau of Mines, Department of the Interior, 1980, 1981, 1982). Includes manganese consumed in ores with greater than 5 percent Mn, ferroalloys, and metal, but not the manganese contained in most iron ores

Box 6-B.—The Role of Manganese as an Alloying Element[a]

Sulfur Control.—In nearly all grades of steel, sulfur is an unwelcome impurity. It is a tramp element that is picked up from the coking coal, fuel oils, and ferrous scrap used in the production of iron and steel. Iron and sulfur form compounds (FeS) at the grain boundaries within steel, causing a detrimental condition known as "hot shortness." Problems arise because FeS has very little structural integrity, being either liquid or extremely plastic at the temperatures encountered during many finishing (hot working) operations. The presence of this strengthless phase as a film along the network of grain boundaries severely weakens steel at high temperatures and causes cracking during fabricating operations. Furthermore, in ferritic grades, FeS causes problems with low-temperature mechanical properties. To minimize these effects, the sulfur content is typically held below 0.05 percent by weight. Manganese is added to react with the remaining sulfur, which would otherwise combine with iron. The globular MnS precipitates formed upon the addition of manganese are solid at typical hot working temperatures and are structurally amenable to hot forming operations. Although it is not a remedy for all sulfur-related problems, manganese generally improves both the high- and low-temperature properties of steel.

Hardenability.—Heat treatment is the most potent method for optimizing the strength and ductility of steel. The cooling rate required to form a given martensite profile during the heat treatment quench is a very important parameter, known as "hardenability," of steel. Additions of the common alloying elements, namely molybdenum, manganese, chromium, silicon, and nickel, facilitate the formation of martensite, thereby reducing the cooling rate requirement and increasing the hardenability of steel. Manganese is a very cost-effective hardenability agent and consequently is one of the most vital alloying elements for influencing the response of steel to heat treatment.

An allied effect of some alloying elements concerns their influence on the shape and distribution of iron carbides in steel. Weld embrittlement can occur if the iron carbides form a continuous film at the grain boundaries during the thermal excursion. Manganese tends to enhance weldability of steel by inhibiting the development of such film.

Wear Resistance.—Manganese, like nickel, lowers the austenite-to-ferrite transformation temperature of steel and is termed an austenite stabilizer. High-carbon steels that remain austenitic at room temperature can be produced by adding manganese to levels greater than 10 percent by weight. Austenitic steels as a class are attractive because their strength increases markedly as they are deformed and they have excellent resistance to fracturing under impact conditions, two properties important for wear resistance. The austenitic manganese grades, called Hadfield steels, display good abrasion and impact resistance and serve in construction, mining, quarrying, oil-well drilling, steelmaking, cement and clay manufacturing, railroading, dredging, and lumbering applications. Other austenitic grades (containing 15 to 25 percent manganese) have been developed for their nonmagnetic properties and high toughness. These high-manganese austenitic steels are suitable for structural uses in strong magnetic fields and at cryogenic temperatures and may replace the stainless steels commonly used in these applications.

Solid Solution Strengthening.—Steel generally becomes stronger when an alloying element is dissolved in the iron phases. This effect is known as "solid solution strengthening." It is a very important means of strengthening ferritic steels, which cannot be strengthened by heat treatment. Alloying elements vary markedly in their potency as solid solution strengtheners. In ferritic steels the order of decreasing effectiveness appears to be: silicon, manganese, nickel, molybdenum, vanadium, tungsten, and chromium. While silicon is highest on this list, it is not used extensively because of an accompanying loss of ductility. Thus, manganese has great utility as a solid solution strengthener.

Recrystallization.—When steel is deformed or heavily worked, its microstructure is altered in a way that is detrimental to the properties of steel. To alleviate problems, steel in this condition is usually annealed, whereupon the microstructure is recrystallized. Manganese slows the rate of recrystallization considerably. This is not a desirable effect and can have negative impacts on the productivity of various steel-treating processes, such as continuous annealing operations.

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[a] The terms ferrite, austenite, and martensite that appear throughout this discussion refer to the various microstructural phases of steel.

MAJOR CLASSES OF STEEL

Steel is produced in a myriad of compositions, and the relative popularity of each grade changes as consumer demands shift. Trends in manganese use vary among the four broad categories of steel: carbon, full alloy, high-strength low-alloy (HSLA), and stainless. All four classes contain manganese, but in differing proportions.

The most widely used systems for designating steels in terms of their chemical compositions are those of the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). These cataloging systems are very similar and are carefully coordinated by the two groups. In addition to the common grades listed by these organizations, steelmakers produce proprietary grades, but the manganese contents of these are comparable. The chemical specifications for a particular grade of steel vary slightly according to the product nature. Specifically, the ranges in plates are a little wider than those for bars, simply because compositional variations due to segregation are greater in the large rectangular ingots used in plate production than in the smaller ingots used for bars.

Carbon Steel.—The main constituents of carbon steels are iron, carbon, and manganese, with manganese present up to a maximum of 1.65 percent. The majority of carbon steels have manganese specifications whose midpoints fall in the range 0.40 to 0.85 percent. The average manganese content of the entire carbon steel category is estimated to be about 0.65 percent, or 13.0 pounds per ton of steel.

Manganese is used in carbon steels primarily for its sulfur control and solid solution-strengthening characteristics. It also improves the heat treating characteristics (hardenability) of these grades, though this is not a major consideration for many uses of carbon steel.

Two types of carbon steel have especially high manganese and sulfur contents in order to improve machinability. These resulfurized and resulfurized-rephosphorized grades typically contain 0.7 to 1.65 percent manganese and find service in applications, such as gears and cams, where considerable machining is needed. The large number of manganese sulfide particles in these steels improve surface finish, enhance metal removal rates, and increase the tool life by facilitating the chip formation process.

Full Alloy Steel.—Alloy steels usually contain more manganese and silicon than do carbon steels and, in addition, may contain other elements such as chromium and molybdenum. The extra alloying additions enhance mechanical properties, fabrication characteristics, or other attributes of the steel. In the more common alloy steel grades, manganese is added primarily for hardenability and less importantly for sulfur control. The average manganese content of alloy steels is estimated to be 0.75 percent, or 15.0 pounds per ton of steel.

There are experimental alloy steels which have not yet been assigned regular AISI-SAE designations. In general, these experimental grades have higher manganese specifications than the standard grades. This suggests that manganese is becoming more popular as an alloying element and that the average manganese content of alloy steels should be expected to increase.

Although most alloy steels contain under 2 percent manganese, several grades containing 10 to 14 percent manganese are used. These are the Hadfield grades, which have excellent abrasion and impact resistance and are used in construction, mining, and other high-wear applications. There are also alloy steels with manganese contents as high as 25 percent that have been developed for use in strong magnetic fields and at cryogenic temperatures.

HSLA Steel.—HSLA steels have been developed as a compromise, having the convenient fabrication characteristics and low cost of carbon steels and the high strengths of heat-treated alloy steels. HSLA steels are generally used in applications such as energy production and automobiles, where savings in weight can be made as a result of their greater strength and atmospheric corrosion resistance and where better durability is desired.

HSLA's derive their superior properties from a variety of alloying elements in relatively low concentrations of 0.2 to 1.6 percent, coupled with controlled rolling and heat treatments. Common alloy additions include manganese, nickel, chromium, columbium, molybdenum, titanium, and vanadium. In comparison with the majority of carbon and alloy steels, the HSLA steels contain greater manganese contents. The limits in the 14 alloys designated by the SAE range from 1 to 1.65 percent manganese, with an average of about 1.1 percent, or an average of 22.0 pounds per ton of steel.

Stainless Steel.—Stainless steels are ferrous alloys that are rich in chromium and sometimes nickel. They are used in a variety of applications requiring good corrosion and oxidation resistance, as well as good strength. Compositional specifications for stainless steels usually do not prescribe minimum manganese levels, only maximum concentrations. Stainless alloy 304, which constitutes roughly 42 percent of the stainless steel produced in the United States, has a manganese specification of 2.0 percent maximum. On the average, stainless steels contain 1.7 percent manganese, or 34.0 pounds per ton of steel.

Several stainless steels, however, contain far more manganese than the average. In part, these alloys reflect the fact that an increase in manganese levels permits a reduction in nickel content. Tenelon steel, containing 14.6 to 16.5 percent manganese, was developed by U.S. Steel Corp. following concern over nickel shortages that occurred during World War II and the Korean conflict.

TRENDS IN THE STEEL PRODUCT MIX AND MANGANESE USE

The average amount of manganese consumed strictly for alloying purposes is being influenced by two major trends. The first is a changing product mix. Steel consumers are using increasingly greater proportions of full alloy, stainless, and HSLA steels, which usually contain more manganese than do carbon steels. Figure 6-2 shows the historical product shares for each of the major steel classes. The classes containing the most manganese, namely, full alloy, HSLA, and stainless steels, are expected to increase their portions of the market. By 2000, the product shares for the various products are expected to be approximately: carbon 80 percent; full alloy 9 percent; HSLA 9 percent; and stainless 2 percent.

The second contrasting trend is the decreasing manganese composition of carbon steels. This is a result of improvements in the steelmaking process, namely, better sulfur removal techniques and more reliable composition control. This effort is driven by economic pressures to conserve raw materials and increase product fabricability. New technologies allow steelmakers to retain the same quality product with less manganese. They can now afford to reduce manganese content to save on raw materials costs and to avoid some of the more unpleasant attributes of manganese, such as the recrystallization problem alluded to in box 6-B. Two manganese reduction techniques are likely to be administered: trimming to the lower end of the specified manganese range for each of the grades and reduction of minimum manganese compositions because less is needed for sulfur control.

Trimming.—Most manganese specifications for steels are listed as ranges. To be on the safe side, steelmakers generally aim for the midpoints of these ranges. Trimming involves aiming for the lower end of the specified range. Improved ladle practice is the key to effective trimming. Better manganese composition control is attainable with improved melt protection, alloy additions packaging, and sensing, analytical, and control instrumentation. Trimming practices could be implemented very quickly in an emergency, especially if operators become better aware of the statistical nature of quality control. The manganese content of steel could be reduced by as much as 0.05 to 0.10 percent with the use of trimming.[28]

Reduction in Specified Manganese Range.—Sulfur specifications of most steels, except for the resulfurized grades, are usually about 0.05 percent maximum. In practice, steels are produced with average sulfur contents of about

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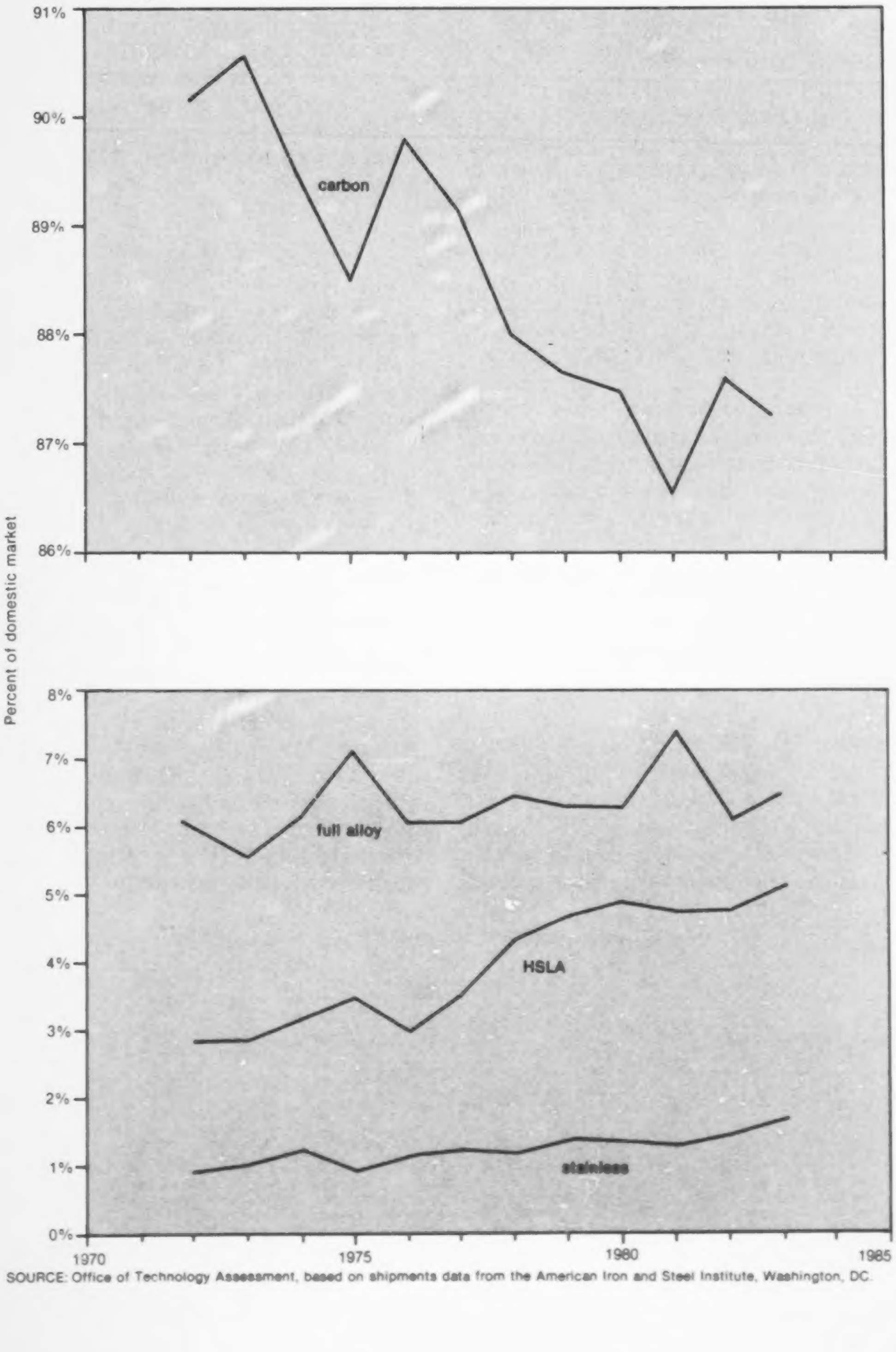
[28] John R. Stubbles, "Conservation Could Cut Steelmaking Requirements," *American Metal Market*, Oct. 20, 1983.

Figure 6-2.—Historical Market Shares for Major Classes of Steel



SOURCE: Office of Technology Assessment, based on shipments data from the American Iron and Steel Institute, Washington, DC.

0.025 percent. Manganese specifications could be reduced to reflect this lower sulfur level.

Technologies such as external desulfurization of blast furnace iron and ladle metallurgy techniques allow steelmakers to reduce the sulfur content of the finished product further still. External desulfurization involves injecting calcium carbide or magnesium metal into the hot metal prior to its introduction to the basic oxygen steelmaking units. Lime is sometimes injected as an auxiliary agent with these desulfurization materials. Implementation of this technique will become almost universal in the domestic industry by 1990. This will reduce the need for desulfurizing during the steelmaking stage and lead to much lower residual sulfur levels in new steel and, eventually, in recycled scrap. Furthermore, ladle injections of desulfurizing agents such as lime, calcium, or rare earths just prior to primary casting reduces the sulfur content below 0.01 percent, and often below 0.005 percent. Ladle metallurgy technologies may not be installed primarily for sulfur reasons, but once they are in place they will no doubt be used to reduce sulfur levels in addition to providing the other benefits.

By 2000, the average sulfur content of steel may be as low as 0.01 or 0.02 percent. This means that less manganese is required in the finished product solely for sulfur control purposes. Even though proportionally higher manganese-to-sulfur ratios are required at lower levels of sulfur, a net reduction in the actual amount of manganese needed is realized by reducing the sulfur content. The manganese content of each grade of steel could probably be reduced by 0.2 percent with the widespread implementation of external desulfurization and ladle technologies. For carbon steels, this represents a 30-percent reduction in the manganese content.

SUMMARY OF TRENDS IN THE MANGANESE COMPOSITION OF STEELS

The effects of the product mix and manganese composition trends on the average manganese content of steel is illustrated by table 6-2. Note that even though the high-manganese alloy products become more pervasive, the average manganese composition is likely to drop from 0.69 to 0.61 percent. That is a reduction of 1.6 pounds (from 13.8 to 12.2 pounds) of manganese for each ton of steel.

Manganese in the Steelmaking Process

On an industry average, almost three times more manganese is added to steel during its processing than ends up in the finished product. When the 11 percent of the manganese additions that comes from in-house recycling is discounted, the overall manganese recovery rate comes to about 39 percent. This section outlines the major trends in steelmaking practice that affect the efficiency of manganese use in the production process.

Table 6-2.—Manganese Content for Major Grade of Steel

	Current (1982)		Forecasted 2000[a]	
	Market share	Manganese content	Market share	Manganese content
Carbon[b]	87.6	0.65	80	0.5
Full alloy	6.1	0.75	9	0.8
HSLA	4.8	1.1	9	1.2
Stainless	1.5	1.7	2	1.7
Total	100.0	0.69	100	0.61

[a] Drastic changes in the balance of economic activity could shift the market shares in 2000 to: 90 percent carbon, 9 percent combined full alloy and HSLA, and 1 percent stainless in the low case; or 70 percent carbon, 27 percent combined full alloy and HSLA, and 3 percent stainless in the high case. An average manganese content of 0.67 percent (high case) might arise from a shift in favor of alloy steels caused by a severe reduction in new construction and manufacture of machinery, vehicles, and containers with a relative gain in the construction of new chemical, petrochemical, coal conversion, and powerplants. Similarly, a substantial shift in favor of carbon steels caused by extremely high demand for new buildings, highways, vehicles, and primary machinery might result in a manganese content of 0.56 percent (low case).

[b] Trimming, together with reductions in the specified manganese range, could cut the manganese content of carbon steels by 0.25 to 0.30 percent. A conservative reduction of 0.15 percent is shown here to account for less than full implementation of these practices.

SOURCE: Office of Technology Assessment based on data from the American Iron and Steel Institute, Washington, DC; and G. R. St. Pierre, et al., *Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an Alloying Element in Steels*, OTA contractor report, February 1983.

PATTERNS OF MANGANESE USE IN STEELMAKING

Figure 6-3 shows the conventional steelmaking sequence, from raw materials preparation to casting and finishing. Manganese enters the process flowstream from five distinct sources: iron ore, fines and waste materials, manganese ore, iron and steel scrap, and ferromanganese.

On an industry average, *iron ore* and *fines and waste materials* contribute approximately 36 percent of the manganese (disregarding that present in ferrous home scrap) ultimately added to the process stream. Iron ores contain approximately 0.16 percent manganese.[27] Although this is a small concentration (and has been declining in recent years), large quantities of iron ore are added to the blast furnace. Fines and waste materials generated by the steel production process contain large amounts of manganese. Though currently there are no satisfactory methods for extracting manganese from the iron and steelmaking slags, dusts, sludges, scales, and other wastes, some plants operate sinter strands to recycle some of these materials. The ore sinter (consisting of partially fused limestone, fine iron ore particles, and steelmaking dust and other waste products) produced in sinter strands can be charged (added) to blast furnaces for hot metal production. Steelmaking slags and dusts consume a large proportion (approximately 42 percent) of the manganese added to the process stream. Slags from both electric and basic oxygen steelmaking furnaces can be charged into blast furnaces, however, basic oxygen furnace (BOF) slags are more commonly recycled in this manner. This is because of the proximity of BOFs to blast furnaces—BOFs are always part of integrated steelmaking facilities, while electric arc furnaces (EAF) are not. According to a 1976 NMAB study, about 40 percent of the BOF slag (containing on average 4.5 percent manganese) produced is recycled to the blast furnace: the rest is discarded.[28] No blast furnace slag is recycled in this manner, but it does find other commercial uses in the brick, aggregate, glass, and bedding industries. There are no reliable data on the overall extent to which manganese is recovered from steelmaking waste materials, but most likely less than 20 percent of the manganese contained in iron and steel industry waste materials is currently recovered for reuse.

Manganese ore charged to the blast furnace accounts for 5 percent (industry average) of the total input of manganese to the processing stream. Charging this ore is a relatively inexpensive way of increasing manganese concentrations to levels beneficial for the processing characteristics of ironmaking and steelmaking.

Iron and steel scrap is charged to the steelmaking furnaces and, to a lesser extent; the blast furnace. The manganese content of home scrap depends on the stage in the steelmaking process at which it is generated. That created at the steelmaking stage contains roughly 0.2 percent manganese, while that coming from casting and finishing reflects the manganese specifications of the product mix of the particular mill in question. Manganese contributions in purchased scrap depend on the trends in the manganese content of steel products, discussed in the preceding section.

Ferromanganese is added to the process stream during the ladle refining stage. Approximately 45 percent (industry average) of the total manganese input is added as ferromanganese. This manganese is not intended to be sacrificed for the sake of processing improvements. Coming late in the steelmaking process, it is intended to bring the level of manganese in the steel up to final product specifications.

Much of the manganese contributed by these five sources does not make it into the finished product, but ends up instead in steel scrap and processing waste products. The percentage that does end up in the finished product is a function of the manganese recovery factors for the various process stages. These recovery factors are dependent on process yield rates and manganese migration characteristics. Poor yield rates result in both large quantities of

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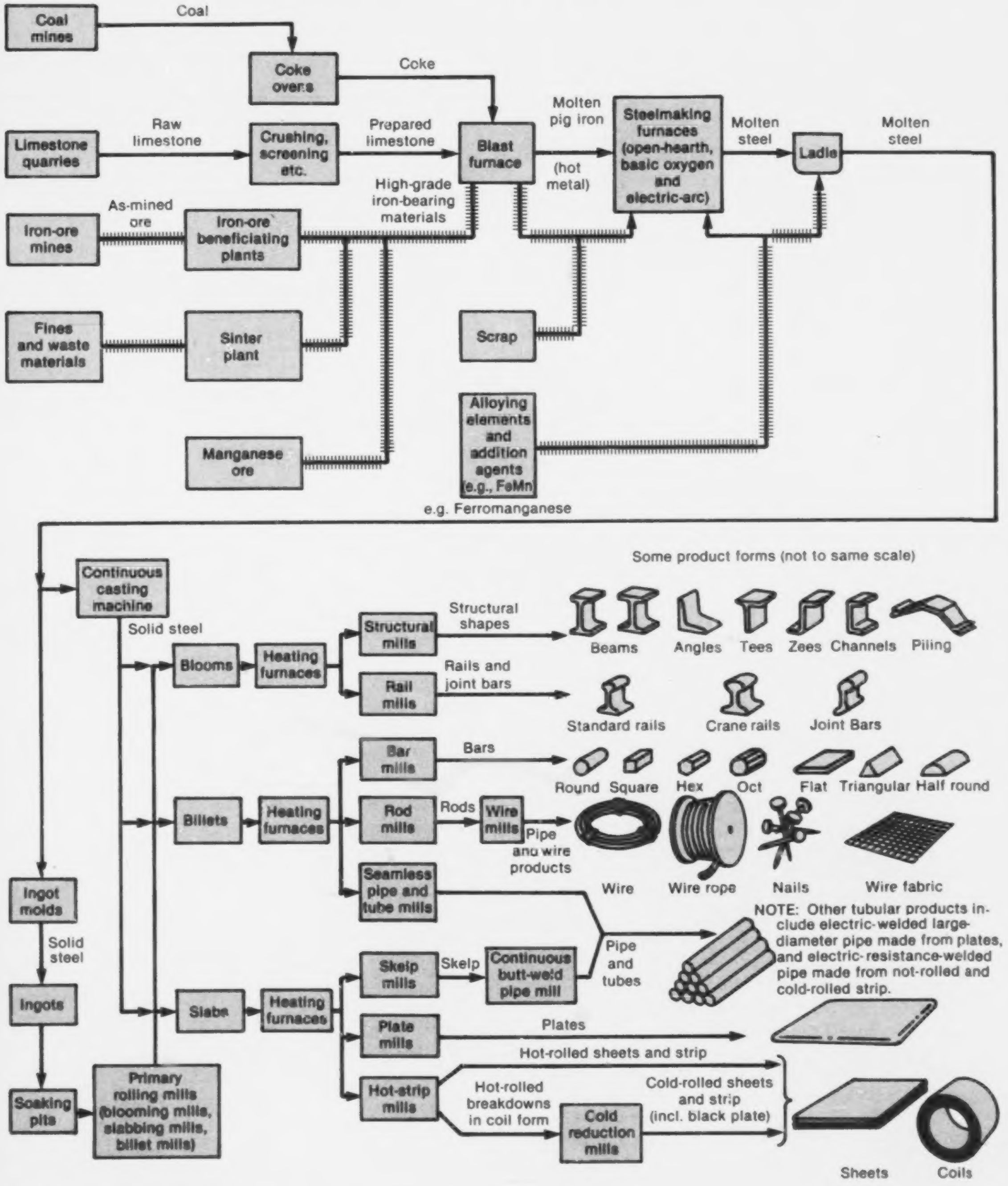
[27] According to the American Iron Ore Association (Cleveland, OH), in 1982, 70 percent of U.S. iron ore consumption was from U.S. sources, while 20 percent was from Canadian sources. On average, the U.S. ores contained 0.12 percent manganese and the Canadian ores contained 0.31 percent manganese.

[28] National Materials Advisory Board, *Manganese Recovery Technology*, publication NMAB-323 (Washington, DC: National Academy Press, 1976).

Figure 6-3.—Flow Diagram Showing the Principal Process Steps Involved in Converting Raw Materials Into the Major Steel Product Forms, Excluding Coated Products


Coal mines
Coal
Coke ovens
Coke
Limestone quarries
Raw limestone
Crushing, screening etc.
Prepared limestone
Blast furnace
Molten pig iron
(hot metal)
Steelmaking furnaces (open-hearth, basic oxygen and electric-arc)
Molten steel
Ladle
Molten steel
Iron-ore mines
As-mined ore
Iron-ore beneficiating plants
High-grade iron-bearing materials
Fines and waste materials
Sinter plant
Scrap
Manganese ore
Alloying elements and addition agents (e.g., FeMn)
e.g. Ferromanganese
Continuous casting machine
Solid steel
Some product forms (not to same scale)
Blooms
Heating furnaces
Structural mills
Structural shapes
Beams
Angles
Tees
Zees
Channels
Piling
Rail mills
Rails and joint bars
Standard rails
Crane rails
Joint Bars
Bar mills
Bars
Round
Square
Hex
Oct
Flat
Triangular
Half round
Billets
Heating furnaces
Rod mills
Rods
Wire mills
Pipe and wire products
Wire
Wire rope
Nails
Wire fabric
Seamless pipe and tube mills
Ingot molds
Solid steel
Ingots
Skelp mills
Skelp
Continuous butt-weld pipe mill
Pipe and tubes
Slabs
Heating furnaces
Plate mills
Plates
Hot-strip mills
Hot-rolled sheets and strip
Hot-rolled breakdowns in coil form
Cold reduction mills
Cold-rolled sheets and strip (incl. black plate)
Sheets
Coils
Soaking pits
Primary rolling mills (blooming mills, slabbing mills, billet mills)

NOTE: Other tubular products include electric-welded large-diameter pipe made from plates, and electric-resistance-welded pipe made from not-rolled and cold-rolled strip.

╫╫╫╫╫╫╫╫ —Shows manganese additions.

SOURCE: *The Making, Shaping, and Treating of Steel*, the United States Steel Corp., Pittsburgh, PA, 1971, adapted by the Office of Technology Assessment to show manganese flows.

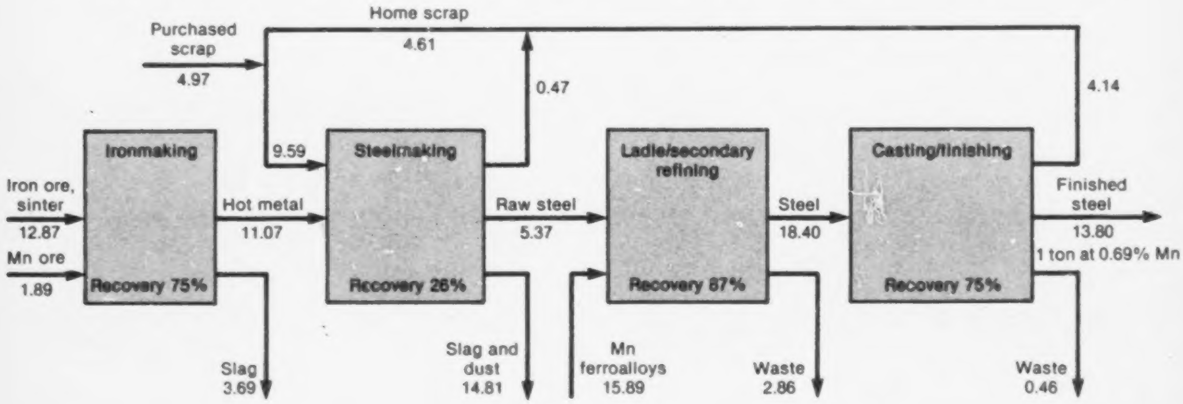
wastes that cannot be recycled, and sizable amounts of home scrap from which additional wastes are produced during recycling. Manganese losses are exacerbated because waste materials such as slags and dusts commonly contain manganese in concentrations greater than those in the steel. Manganese, as well as many other alloying elements, often migrates to the process wastes. Sometimes this segregation of elements between the steel and the wastes is intentional, as during the steelmaking stage when manganese is used to react with dissolved oxygen and carry it into the slag.[29] In a sense, these are "sacrificial losses." In other instances the segregation is an unwanted consequence of the process chemistry. Regardless of the intent, this manganese migration causes the recovery factors to be lower than the yield rates.

TRENDS IN STEELMAKING TECHNOLOGY

Figure 6-4 shows the current pattern of manganese use in the production of one ton of steel product. Of the total manganese consumed in the steelmaking process, 39 percent is embodied in the finished steel product, and 61 percent is lost in slags, dusts, and wastes. Note that 13 percent of the manganese inputs are recycled as home scrap, generated principally during the casting and finishing steps. The flows in the figure are industry averages and do not reflect operations in any particular steel plant. They are aggregates based on the current mix of equipment and operating characteristics for the industry. Shifts in this mix of steelmaking technologies are expected to change the manganese flow pattern.

Ironmaking.—From 50 to 80 percent of the manganese charged to blast furnaces is retained in the molten pig iron. Typically, the average recovery rate is 75 percent. The remainder is lost to blast furnace slag, which is not recycled or processed for its manganese content. Although construction and operation of direct reduction ironmaking plants will con-

Figure 6-4.—Current Pattern of Manganese Use in Steelmaking (pounds of manganese of finished steel)



*Recovery with respect to ferromanganese additions is assumed to be 82 percent, while complete recovery of Mn is assumed for raw steel.

SOURCE: Office of Technology Assessment; and G.R. St. Pierre, et al., *Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an Alloying Element in Steels*, OTA contractor report, February 1983.

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[29] Oxygen dissolved in molten steel reacts with carbon to produce gaseous carbon monoxide, which, when trapped during ingot solidification, causes defects known as blowholes. This problem can be avoided by reducing the oxygen content of the steel with the addition of elements that react with the oxygen and carry it off to the slag. Manganese, aluminum, and silicon are the most important of the deoxidizing agents. Though a weak deoxidizer by itself, manganese enhances the deoxidizing capacity of silicon. Moreover, the presence of manganese oxide in the slag helps to develop proper slag characteristics, in part through more rapid dissolution of lime. If the manganese content of the steelmaking charge is too low, additional slag fluxes containing fluorspar, which is considerably more expensive than ferromanganese, must be used.

tinue, particularly in certain parts of the world, e.g., the Middle East, Mexico, South America, and Soviet Union, where natural gas is abundant, the principal source of domestic crude iron will continue to be the blast furnace.

Over the next few years, the trend to shut down the oldest and least efficient blast furnaces and to upgrade the better furnaces will continue. Furnaces are upgraded in a number of ways; including modifications of the charging systems and relining configurations, adoption of improved hot blast, additive, pressurization, and tapping procedures, and installation of better instrumentation and control equipment. All of these developments taken together will increase the operating performance of blast furnaces but are unlikely to have a major effect on manganese use.

Manganese retention in the blast furnace can be expected to decrease somewhat from its current value of 75 percent because of the use of more acidic slags allowed by external desulfurization. However, this should be offset by the opportunity to include more manganese-bearing steelmaking slag (primarily for its iron, lime, and flux content, but also for manganese) in the blast furnace charge.

Steelmaking.—Currently, manganese recovery in BOF steelmaking ranges from 20 to 50 percent, depending on the final carbon content and temperature of the melt (manganese recovery improves with increases in both). Recovery in electric steelmaking is substantially greater. The proportion of steel produced in EAFs is increasing relative to BOFs. The current ratio of EAF steel to BOF steel, roughly 30:70, is expected to increase to 40:60 by 2000. This not only improves the average manganese recovery rate, but also increases the average ferrous scrap charge rate. Scrap is typically 100 percent of the charge to EAFs while only 30 percent to BOFs. Thus, greater use of EAFs increases the recycling of manganese.

Operating practices for both EAFs and BOFs are changing. The basic oxygen processes are undergoing dramatic changes with the incorporation of bottom blowing and inert gas mixing techniques. Manganese recovery will probably increase to the range of 40 to 60 percent over the next few years as a result of these and other changes, such as separate desiliconization and better control of the charge and slag. Manganese recovery in EAFs is expected to improve somewhat over the next few years from better charge materials, reduced oxidation during high-speed meltdown, improved end-point control, and greater use of secondary and ladle refining.

Based on current operating practices and mix of BOF and EAF steelmaking, the average manganese recovery of the steelmaking stage is estimated to be 26 percent. The increasing use of EAF steelmaking and improvements in operating characteristics are expected to improve this average recovery rate to 42 percent by 2000.

Ladle and Secondary Refining.—The role of ladle and secondary refining has grown rapidly during the past few years. In stainless steel production, adoption of AOD processing, which is a secondary refining process, is almost universal. For low-alloy and carbon grades, deoxidation and desulfurization procedures have been greatly improved with the increased use of argon shrouding of steel surfaces and pouring streams. In addition to the trimming benefits mentioned in the previous section, these processes capture the manganese content of ferroalloy additions to a much higher degree and reduce reoxidation loss during subsequent pouring. These improvements are expected to raise the recovery of manganese from the ferroalloys from 82 to 90 percent which raises the overall manganese recovery rate of the process from 87 to 95 percent.

Casting and Finishing.—The benefits of continuous casting have been fully established. Continuous casting leads to overall cost savings as well as improved product quality (cleanliness, homogeneity), reduction of energy requirements and decreased metal loss (scaling) during ingot reheating. In addition, it gives greater yields of steel products from raw molten steel.[30]

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[30] The ingot-to-slab yield of conventional ingot casting operations varies greatly according to the nature of the products. Owing to large shrinkage cavities, the yields for killed grades

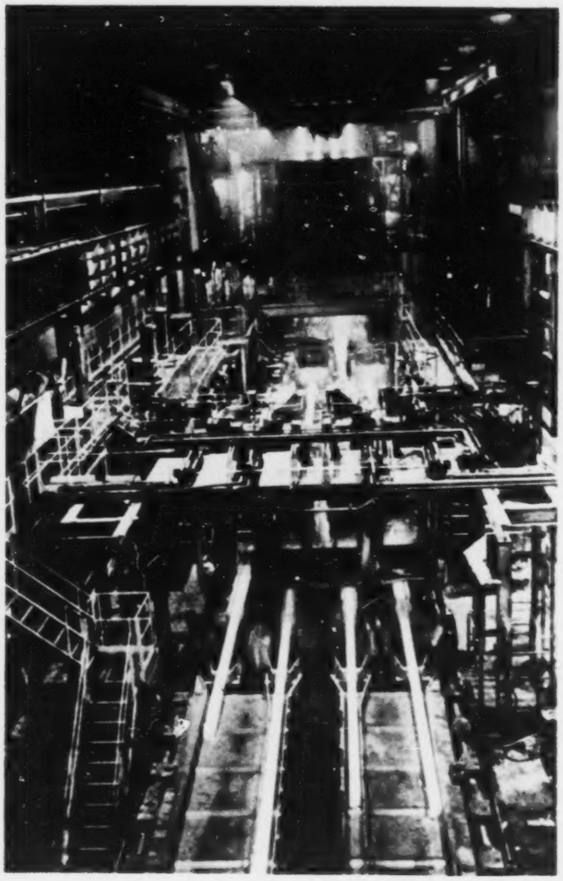

Photo credit: American Iron and Steel Institute

Continuous casting of steel is one of a variety of improved steelmaking technologies that conserve manganese

From the manganese standpoint, increased yield means that less home scrap must be recycled through processes where there are irrecoverable losses. In 1982, about 29 percent of domestic steel was continuously cast. This rose to about 36 percent in the first half of 1984, and is likely to increase to 70 percent by 2000. Manganese losses are not a major problem at the casting stage because there is very little migration of manganese to the waste products.

Direct rolling of hot slabs and billets from continuous casters has been demonstrated in several plants throughout the world. By eliminating the cooling and reheating steps, this technology offers potential for further improvements in metal recovery as well as energy savings.

Based on the trends toward greater use of continuous casting and direct rolling, the yield rate during casting and finishing operations is expected to increase from its 1982 value of 75 to 85 percent by 2000.

Summary of the Effects of Processing Trends

The current and expected yield rates and manganese recovery factors for each stage of the steelmaking process are shown in table 6-3. These embody the shifts in technology discussed above. The overall manganese recovery rate increases from 39 to 49 percent.

Outlook for Manganese Use in the Steel Industry

The expected impacts of steel product and processing trends on the manganese use pattern in 2000 are outlined in table 6-4. High and low cases are included in the table to illustrate the effects of different product mixes and various schedules of investment in new equipment.

A 12-percent net reduction in the average manganese content of steel (from 13.8 to 12.2 pounds per ton) is expected to accompany the contrasting shifts towards the greater use of high-manganese products and the increased attention to trimming. Trends in steelmaking technology are expected to cut average manganese consumption losses from 21.8 to 12.6 pounds per ton of steel, a reduction of 42 percent. In addition, these technology changes increase the role of purchased ferrous scrap (available domestically) as a source of manganese.

Most importantly, these product and process trends decrease the per-ton-of-steel requirement for manganese in the form of ferroalloys and manganese ore by 47 percent, from 17.8 to about 9.5 pounds. Depending on the product mix and the rate of adoption of the process improvements, the requirement could be

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can be quite poor, even as low as 70 percent. The yields for rimmed products are substantially better. On an industrywide basis, the average yield of ingot casting operations is estimated to be approximately 87 percent. Continuous casting, the more modern and more desirable process, has a yield of approximately 96 percent.

Table 6-3.—Parameters Affecting Manganese Retention in the Steelmaking Process

	Current (1982)		Expected 2000	
	Yield rate (percent)[a]	Manganese recovery factor (percent)[b]	Yield rate (percent)[a]	Manganese recovery factor (percent)[b]
Ironmaking (blast furnace)	100	75	100	75
Steelmaking (BOF and EAF)	85	26	90	42
Ladle and secondary refining[c]	100	87	100	95
Casting and finishing	75	75	85	85

[a] Yield rate = (lbs of iron in primary output product) ÷ (lbs of iron in input materials).

[b] Recovery factor = (lbs of manganese in primary output product) ÷ (lbs of manganese in input materials).

[c] Recovery factors for ladle and secondary refining are based on 100 percent recovery of manganese in molten steel combined with 82 percent (current) and 90 percent (2000) recovery of the manganese in ferroalloy additions.

SOURCE: Office of Technology Assessment; and G. R. St. Pierre, et al., *Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an Alloying Element in Steels*, OTA contractor report, February 1983.

Table 6-4.—Current and Projected Manganese Consumption in U.S. Steel Production
(all figures in pounds of manganese per ton of steel product, except where noted)

	Current (1982)	Projected, Year-2000		
		Expected	Low	High
Total manganese use (excluding home scrap)	35.6	24.8	20.6	30.4
Outputs:				
Retained in steel products	13.8	12.2	11.2	13.4
Losses (slag, dust, waste)	21.8	12.6	9.4	17.0
Inputs:				
Manganese ore	1.9	1.2	1.0	1.5
Manganese ferroalloys	15.9	8.3	5.5	12.2
Iron ore and sinter	12.9	8.5	7.1	10.1
Purchased ferrous scrap	5.0	6.8	6.9	6.6
Overall manganese recovery rate (ignoring home scrap) (percent)	39	49	54	44
Assumptions:				
Manganese content of steel (percent)	0.69	0.61	0.56	0.67
Percentage of molten steel produced in EAF processes (percent)	28	43	48	38
Manganese recovery rates and yield rates:				
Ironmaking:				
Recovery (percent)	75	75	75	75
Yield (percent)	100	100	100	100
Steelmaking:				
Recovery (percent)	26	42	50	34
Yield (percent)	85	90	93	87
Ladle and secondary refining:				
Recovery (percent)	87	95	98	90
Yield (percent)	100	100	100	100
Casting and finishing:				
Recovery (percent)	75	85	90	80
Yield (percent)	75	85	90	80

SOURCE: Office of Technology Assessment; and G. R. St. Pierre, et al., *Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an Alloying Element in Steels*, OTA contractor report, February 1983.

as low as 6.5 pounds per ton or as high as 13.7 pounds per ton.

Automotive Catalysts

Since 1975, the catalytic converter (now used on most cars to control air pollution) has become the single largest use for PGM in the United States, accounting for over 30 percent of all PGM consumption. Platinum, palladium, and, since 1981, rhodium are the active ingredients used in converters to control hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emission levels. In addition, about 10,000 tons of chromium are used annually in the stainless steel shell of the catalytic converter—about 1.5 percent of U.S. chromium consumption, and 3 percent of chromium consumption in stainless and alloy steels.

As a result of nearly a decade of using catalytic converters, a very large "above-the-ground mine" of PGM has accumulated in the Nation's automotive fleet—some portion of which can be retrieved each year through collection and recycling of converters from scrapped cars. As the fleet of converter-equipped cars ages, the inventory of PGM available from scrapped cars will grow very rapidly through the 1980s and into the 1990s. If effective retrieval and recycling of catalytic converters from these scrapped cars occurs, U.S. PGM imports can be reduced appreciably below what they would be otherwise.

The current level of PGM recovery from catalytic converters is low, in part because converter-equipped cars are only now appearing at scrapyards in large numbers. This may change in the near future: the average life of a car is about 9 to 10 years, so post-1975 model cars (the first year in which production model cars were equipped with a converter on a nationwide basis) will comprise an increasing proportion of scrapped vehicles.

Figure 6-5, based on projections prepared for OTA by Sierra Research and Energy and Environmental Analysis, Inc., compares the maximum theoretical potential for catalyst recycling from scrapped cars with projected PGM demand for new vehicles through 1995.[31] As shown, the theoretical potential for recycling will grow from about 115,000 troy ounces in 1983 to over 800,000 troy ounces in 1995. Assuming a 50 to 60 percent recovery rate, catalytic converter recycling could add 400,000 to 500,000 troy ounces annually to domestic PGM supplies by the mid-1990s. This compares with new vehicle demand of 770,000 troy ounces in 1983, which is projected to grow to 1.4 million troy ounces in 1995. Less economic incentive exists to recycle chromium values from the stainless steel shell of catalytic converters.

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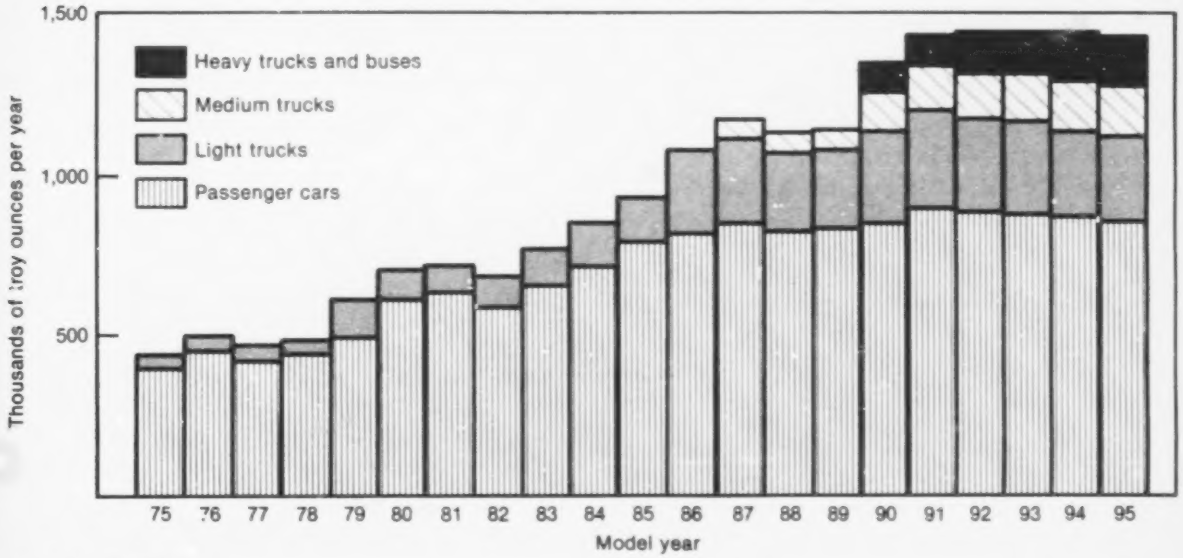
[31] Sierra Research and Energy and Environment Analysis, Inc., *Critical Metal Consumption in Automotive Catalysts, Trends and Alternatives*, report prepared for OTA, December 1983. Much of the analysis and data in this section are derived from this report.

Figure 6-5.—PGM Demand by Vehicle Category



SOURCE: Sierra Research.

However, if the above recovery rates are assumed, 5,000 to 6,000 tons of chromium could be provided annually.

It should be noted that considerable uncertainty surrounds the projections in figure 6-5—especially those related to PGM requirements for new vehicles. The projections for new vehicle PGM requirements are for the total U.S. market for vehicles, without assumption about prospective import levels. The projected demand is based on medium growth assumptions about vehicle sales. The projections also reflect anticipated new emission control standards expected to be applied to vehicles in the 1985-90 period. Changes in the timing and nature of these standards would change the projections. Readers are referred to chapter 3 for further discussion of the projected growth in PGM use for vehicle emission control.

Somewhat less uncertainty surrounds the projections of PGM potentially available for recycling through 1995. Cars already on the road will constitute the great majority of vehicles scrapped during the projection period. Actual recycling levels will be considerably lower than the theoretical potential, due to losses of PGM while cars are in service, and at each of the several steps entailed in recycling. Estimates of PGM losses from catalytic converters while cars are in service range from under to well over 10 percent, and this is not reflected in figure 6-5. According to the Automotive Dismantlers and Recyclers Association (ADRA), only 70 to 80 percent of the 10 million cars that are "detitled" in a normal scrappage year (1979 was the last such year) actually reach dismantling yards where the converter can be removed for recycling. Moreover, not all dismantlers remove the converter from the car before it is compacted into a bale or shredded. Some PGM shipped to a refiner (perhaps 10 percent) is lost in refining. Hence potential addition of PGM to U.S. supplies from catalytic converter recycling probably will only be 50 to 60 percent of the levels shown in figure 6-5. Actual levels or recycling will depend on economic incentives and the effectiveness of the collection networks that are established.

Structure of the Recycling Industry

Among the types of firms that have an interest in the growing market in PGM recycling are primary and secondary PGM producers, manufacturers of emission control devices, scrap processors and dealers, automotive dismantlers, muffler shops, collectors and distributors of used automotive parts, and decanners--a new specialized business that has arisen around the catalytic converter. There are no major technological barriers to recycling of either PGM or chromium values from catalytic converters, and the number of firms involved in catalyst collection networks is expected to increase gradually as the market continues to grow. In addition, the industry appears capable of responding quickly to price increases, so that recycling could be greatly expanded if there were a supply disruption.

The industrial refining capacity needed to recycle PGM from automotive catalysts taken from scrapped cars is already in place. Major domestic PGM refining facilities operated by Gemini Industries and Johnson Matthey are available for converter recycling. These facilities are able to recover PGM values both from new catalysts rejected by automakers and from scrapped converters. Domestic scrap processors are also able to recycle the stainless steel shell of the catalytic converter as a scrap feed. Steps entailed in recycling spent catalysts are described in box 6-C.

Institutional factors could impede recycling levels, however. Three categories of catalytic converters are potential sources of PGM for recycling: unused catalysts that fail to meet product specifications, rejected and damaged catalysts from operational vehicles, and spent catalysts from scrapped vehicles. Of these, the last category represents the largest future supply of PGM, but also presents the greatest collection difficulties. Reasons for this include fluctuating PGM prices, the fragmentation of the automotive dismantling industry, and a lack of effective linkages between refiners and dismantlers.

The availability of automobile catalysts for recycling is affected by several factors. Some

Box 6-C.—How Catalytic Converters Are Recycled

With the advent of the catalytic converter, a new industry has evolved to recover PGM values from scrapped automobile catalysts. From a technical standpoint, there are few barriers to refining PGM from spent catalysts. In the mid- and late 1970s, facilities were set up to recycle unused catalysts that failed to meet product specifications. This gave refiners the experience needed to take advantage of the far greater amount of PGM that can be recovered from scrapped cars. However, the business of organizing effective collection systems has proven surprisingly complex.

Part of the reason for this is that catalytic converters are not uniform products whose value can be easily identified. In 1982 model cars, for example, there is a 10-to-1 range in PGM content among different converter models—0.33 troy ounces on heavily loaded converters down to 0.03 troy ounces on lightly loaded converters. (This wide range in catalyst loadings is probably not a measure of the efficiency of the converter in reducing emissions; instead the heavily loaded catalysts are probably installed in car models with engines that produce higher than average emission levels prior to catalytic treatment.) Many of the converters, especially on older model cars, have catalyst pellets (some of which may be lost in the course of vehicle operation), while others are monolithic, with the catalyst deposited on a secure substrate. Chromium content in the stainless steel shell of converters also varies from 1.5 to 3 pounds. Finally, early model converters contained just platinum and palladium, but more recent "three-way converters" contain rhodium as well.

Before lots of spent catalysts actually arrive at a refiner for reprocessing, several separate firms—including automotive dismantlers, collectors, decanners, and scrap processors—can be involved. Some of these firms specialize in collection of certain types of converters and do not purchase other types. Some work under an arrangement with refiners. Others are independent.

Preliminary sorting is done by the automotive dismantler after the converter is removed from the car by torching or cutting or, in the case of larger shredding operations, popped off with a forklift. Some converter containers contain little or no catalyst. Spent catalysts commonly contain at least some lead, which is particularly undesirable to refiners, and moisture, which can also affect chemical analyses and reprocess smelting. If the scrapped converter is sold to a collector, it may be visually inspected by the collector for catalyst content. However, the dismantler may choose not to sell the converter to a collector and may instead stockpile it, waiting for a price increase, or keep it for sale to retail customers.

The decanner (who may be the collector or the the auto dismantler) removes the catalyst substrate from the stainless steel container. After it has been removed, the catalyst is placed in drums to prevent further moisture accumulation, and is sold to a refiner. The stainless steel shell of the converter may be sold to a scrap processor, some of whom also may serve as collectors or decanners.

Both the quality and quantity of the catalyst play major roles in determining the price paid to decanners by refiners. Some require a minimum shipment of 3,000 pounds of catalyst substrate. Bonuses may be paid for shipments that exceed average PGM content, while penalties may be charged for below-average shipments. A partial payment for the catalyst may be paid upon receipt, with the balance reserved until actual assay, often 6 to 10 weeks later.

Once the spent catalysts are accepted by the refinery, several commercialized processes can be used to recover the PGM. Two major domestic refiners—Gemini and Johnson Matthey—use proprietary hydrometallurgical processes to separate the substrate from the PGM through an acid or alkaline leach. Final removal of the PGM from the resulting leach liquor or sludge is complex, involving as many as 18 separate steps, but can recover more than 90 percent or more of the PGM. Scrapped catalysts can also be run through copper or nickel pyrometallurgical refining circuits to recover about 90 percent of the PGM. This approach was taken by Inco, a large Canadian nickel and copper producer, in 1980 and 1981, when PGM prices were high, but has been subsequently discontinued.

In addition to recycling PGM, interest is growing in the possibility of "regenerating" spent catalysts. This would involve leaching out lead and other impurities and washing additional PGMs as required, while keeping the substrate and shell intact.

cars are simply abandoned; some are taken directly to a scrap processor for baling or shredding, where the value of the PGM (and chromium in the converter shell) is lost; others are exported. As a result, about 20 to 30 percent of all cars are never taken to a dismantler.

Even those cars that reach dismantling yards will not necessarily have their converter removed. According to the ADRA, the majority of automotive dismantling firms have less than 10 employees. With a 1983-84 scrap price of only about $5 to $7 per converter, not all dismantlers feel it is worth their employees' time to remove the converters, while others may be stockpiling the catalysts until prices rise. A 1982 survey of some ADRA members and some unaffiliated dismantlers by Arthur D. Little, Inc., found that 12 percent of those firms responding to the survey leave the majority of converters on the car.[32] However, ADRA members and other respondents may not be representative of the industry as a whole. Small firms that lack the resources to participate in the trade association may be more likely to leave converters on cars.

Providing refineries with a steady supply of scrapped converters has also been a problem. The auto dismantling industry is highly decentralized, having 11,000 separate firms, according to ADRA, while only a few large firms are involved in refining the catalyst. As more actors have become involved, intermediary firms specializing in collection and decanning have arisen either independently or in affiliation with refiners. Because refiners are trying to assemble economic volumes for recovery, a premium is paid for larger volumes of material. When a sufficient number of converters has been collected by a dismantler they are sold to collectors and/or decanners. Usually a minimum of 50 to 100 converters is required to deal with a large collector.

Collectors accumulate small lots of whole converters within a particular region and sell larger lots at higher prices to decanners. Some collectors are also decanners. Often, collectors have regular truck routes to purchase converters from dismantlers and, in some cases, from shredding yards.

Decanners purchase large lots of whole converters, and separate the catalyst's substrate from the housing or shell, usually by shearing the canister in half. The pellets and honeycombs are packed separately in 55 gallon drums. Owing to the low nickel content and accumulated impurities, the 409 stainless steel used in the converter shell has a low market value ($110 per ton in late 1983). Nevertheless, the shell represents an additional source of value to the decanner.

The quality of catalyst material sold to refiners, as well as the volume, plays a major role in determining the price paid to decanners. Decanners are cautioned not to include contaminated units. Pure white catalyst substrates indicate burnout and loss of the PGM coating. Catalysts coated with lead and oil are also undesirable in the refining process.

Auto dismantlers would prefer to have more than one purchaser (collector or core buyer) for used converters to ensure the best price and most reliable pickup, while refiners prefer to purchase large quantities of catalysts from one collector. During periods of low platinum prices, both dismantlers and collectors may stockpile catalysts, waiting for prices to rise. In the long term, many of the problems apparent in the early stages of the industry's evolution may be overcome, due to the increased numbers of scrapped cars equipped with converters available for recycling and possible increases in PGM prices.

USED AND RECONDITIONED CATALYTIC CONVERTERS

A recent development in the automotive dismantling industry has been the emergence of a market for secondhand catalytic converters bought as replacement parts. The exact magnitude of this market is not known, but a recent survey in California found that about 80,000 secondhand converters were used annually in the State.[33] Most of these secondhand converters were obtained from parts distributors who purchased them from auto salvage dealers at a somewhat higher price (averaging $7 per unit) than is typically paid by refiners. Auto dismantlers also sell converters directly to retail customers as used parts, often at a price of $45 to $70.

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[32] Automotive Dismantlers and Recyclers Association, *Profile: Automotive Dismantling Industry*, published in cooperation with Arthur D. Little, Inc. (Washington, DC: Automotive Dismantlers and Recyclers Association, 1983), p. 12.

[33] Mobile Source Control Division, *Used Catalytic Converter Survey* (El Monte, CA: State of California Air Resources Board, July 1983), memo.

The apparently growing market for secondhand converters concerns some refiners since it adds an additional layer of competition in their efforts to secure a supply of catalysts for recycling. The competition is great because this market is an important source of income to dismantlers, who typically obtain three-fourths of their income from sales of used parts, while scrap sales form only a small part of their business.

An emerging issue associated with the apparently growing market for secondhand catalytic converters concerns possible reuse of defective catalysts in cars. While secondhand converters are substantially cheaper to the motorist than new replacement converters, which range in price from $170 to $320, many secondhand converters are defective, and will therefore adversely affect air quality if they are installed in cars.

It is not possible to determine whether a used converter is operating properly without emissions inspection and testing. A gradual deterioration in catalyst efficiency occurs over time, and most automakers guarantee the converter for only 50,000 miles. In addition, leaded gas, which destroys the emissions control capability and the platinum metal values in the catalysts, is often used in converter-equipped cars and trucks. Occasionally this happens inadvertently, if fuel supplies in a filling station become contaminated or are switched. More often, motorists deliberately and illegally misfuel because of lower price and perceived improved performance of leaded gasoline.

Currently, overall procedures for testing and certifying secondhand catalytic converters are not in place. Although the U.S. Environmental Protection Agency has issued voluntary aftermarket part self-certification regulations, these relate primarily to new replacement converters. However, methods to test used catalytic converters are under development by a major muffler firm, using the voluntary self-certification regulations. The entire issue associated with use of secondhand converters is highly complex, and is likely to be an increasingly important concern in both emission control programs and recycling efforts in the years to come.

ALTERNATIVES TO PGM USE IN THE CATALYTIC CONVERTER

At present, PGM use in the catalytic converter is the most effective means for meeting emissions control standards under the Federal Clean Air Act. Near-term (before 1995) alternatives to PGM use in the catalytic converter are not promising. Most currently developed alternatives would entail major loss of fuel economy and/or a need to relax automotive emissions standards. These problems could be overcome, given several years lead time, but there is no persuasive reason at this time for auto makers to pursue these alternatives.

Increased use of diesel engines could also reduce the need for PGM catalysts. However, while diesels do not currently require converters to reduce carbon monoxide and hydrocarbons, they do produce substantial amounts of particulates. A more stringent particulate national emission standard for diesel-fired light-duty vehicles (cars and light trucks) is expected to take effect in 1987. Some manufacturers are expected to employ a platinum-catalyzed trap oxidizer to meet the standard. The other most likely alternative—a trapping system which uses onboard dispersing of fuel additives—would not entail PGM use. A particulate emissions standard for heavy duty vehicles, if adopted as expected in 1990, most likely will require PGM catalyzed trap oxidizers, because additives are unlikely to prove practical over the long lifetime of these engines. (In the projections shown in figure 6-5, it was assumed that half of the light duty diesel vehicles will use a PGM particulate trap when the standards take effect—1986 in California and 1987 nationwide—but that all California light trucks and diesels would use particulate traps to meet the more stringent State standard expected in 1989.

It was also assumed that all heavy duty diesel engines will require PGM particulate traps to meet the anticipated 1990 national standard.)

Even in the longer term (beyond 1995), PGM use for emission control is likely to continue, although use of substitute materials, more efficient loading of PGM, and basic changes in the overall design of automobiles, might reduce per vehicle requirements. At present, the major auto makers foresee no major change in total loadings of PGMs used in converters, although ratios of platinum, palladium, and rhodium may change. Alternative base metal catalysts are not likely to substitute for PGM catalysts, unless breakthroughs overcome major technical problems that make them less effective in emissions control.

Downsizing of engines to meet federally mandated fuel efficiency standards, coupled with improved catalyst formulations, may reduce the amount of PGM needed to treat emissions effectively. With long-term increases in gasoline prices, downsizing may occur regardless of whether Federal standards are extended beyond 1987. Alternative trends in downsizing to the year 2000 are discussed in detail in the 1982 OTA assessment, *Increased Automobile Fuel Efficiency and Synthetic Fuels.*[34]

Considerable speculation exists about possible future use of alternative automotive engines that are radically different from those used today, such as the automotive gas turbine (AGT) and stirling engines. These engines would have very low emissions levels, thus reducing emission treatment needs. As is discussed in chapter 7, technical problems (including development of reliable ceramic parts) make it unlikely that the AGT will be widely used until after the year 2000, if then. Alternative fuels, such as methanol, are also under consideration as a principal fuel for some automobiles. Emissions from cars retrofitted to burn methanol do not meet current standards without catalytic treatment. Moreover, emission tests on methanol-burning cars show relatively higher levels of aldehyde emissions than for gasoline-powered cars. Aldehyde emissions can be reduced by catalytic after treatment. Aldehydes are not covered in current emission standards, so new standards could be required if methanol is widely used.

STRATEGIES FOR EMISSION CONTROL IN A SUPPLY DISRUPTION

PGM recovered from catalytic converters can be reprocessed into virtually any form needed by industry. In a major supply disruption, automotive catalyst production could be temporarily curtailed, thus permitting PGM that is recovered from scrapped catalytic converters to be diverted to more critical economic and military uses. PGM use in catalytic converters is critical to controlling air pollution, but is not otherwise a critical component of the U.S. economy. In a national emergency, a temporary discontinuance of PGM use in the manufacture of new catalytic converters, together with intensified recycling of PGM from scrapped cars, would insulate the most critical economic uses from the effects of a supply disruption.

As a result, U.S. ability to contend with a supply cut-off has theoretically improved, owing to reliance on PGMs for emission control, even though PGM imports have increased because of it. Use of such an emergency strategy, however, would have major impacts on the emissions control program established under the Federal Clean Air Act.

Alternative strategies for auto makers and Government officials for dealing with a near-term curtailment of PGM supplies were addressed in the report prepared for OTA by Sierra Research and Energy and Environmental Analysis, Inc. This analysis demonstrates that practical alternatives to the catalytic converter are not currently available that could meet both current emissions and fuel economy standards. In a near-term supply disruption in which no PGM was available for emissions control, auto makers would probably have little alternative except to build cars without catalytic converters—although this could be accompanied with a requirement for retrofit when the shortage ended.

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[34] *Increased Automobile Fuel Efficiency and Synthetic Fuels* (Washington, DC: U.S. Congress, Office of Technology Assessment, September 1982), p. 17.

In a supply disruption lasting 1 to 3 years, recalibration of new vehicles for lower emissions without catalyst use would be feasible. This could entail programming of fuel metering systems for leaner operation to reduce hydrocarbon and carbon monoxide emissions. In addition, retarding spark advance to further reduce HC and NO_x emissions could be undertaken. These changes would not entail substantial design changes or development costs. Although some fuel economy penalties would be incurred, average new car emission levels approximately equal to 1977-79 standards could be achieved in this way. Since computer controlled systems are now used in many new vehicles, retrofitting after the disruption would be comparatively simple, entailing replacement of a computer chip or (more likely) the entire electronic control unit of the vehicle.

With an intensive program of research and development (R&D), according to the analysis, alternative emission control systems that do not use PGM but would approach current emissions and fuel economy standards could probably be developed. However, this would require at least 5 years and is unlikely to be undertaken by auto makers simply out of concern about future supply disruptions.

Development of such technology could be necessary in the event of a "worst case" supply disruption of several years' duration in which national emergency requirements could not be satisfied from recycled PGM alone. Under such dire circumstances, pressures would mount to recover PGM from operating vehicles.

The total current in-service vehicle fleet contains roughly twice as much PGM as was consumed for all uses domestically in 1982. This will more than double by 1995—to a total of 9 million troy ounces of PGM, some portion of which could be recovered in a dire emergency through Government programs aimed at removing some catalytic converters from the in-service automotive fleet.

Ultimately, both the objectives of national preparedness in the event of a supply emergency and national air quality objectives could best be served if contingency planning were undertaken to determine under what circumstances, and in what way, allocation of PGM would occur in a supply emergency. Such planning could also be used to identify emission control strategies available to auto makers in the event that supplies of PGM are not available for manufacture of catalytic converters.

Other Conservation Opportunities

Petroleum and Chemical Catalysts

Both PGMs and cobalt are extensively used in the petroleum and chemical industries as catalysts. PGM use in these catalysts is already highly efficient so that only limited improvements in current patterns of use can be made in the foreseeable future. The PGM contained in industrial catalysts is generally retained in ownership by the user firm and is refined or regenerated on a toll basis by a specialized recycling firm. This system is highly efficient: Of the 235,000 troy ounces of new PGMs that were purchased for petroleum and chemical industry catalyst applications in 1982, only about 10 percent was to make up metal losses during processing and toll refining; the rest was to meet new production needs. The only catalysts that are not now recycled contain less than 0.05 percent PGMs. Recovery of PGM values from these catalysts is technically feasible, but the refining costs (including transportation costs to and from the refinery) exceed the contained metal value.

In the case of cobalt-containing catalysts, however, major opportunities exist to increase recycling levels, particularly in the case of the cobalt contained in spent petroleum refining catalysts. Although some other metals are now reclaimed from these spent catalysts, cobalt values are not.

Overall national trends in cobalt catalyst use (exclusive of paint dryers) were extensively analyzed for OTA by the Inco Research & Development Center, Inc.,[35] and are summarized in table 6-5. This information, obtained from estimates provided by industrial sources in late 1983, is believed to be the most up-to-date and detailed information about these trends that is publicly available.

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[35] F. J. Hennion, J. J. deBarbadillo, J. H. Weber, and G. Alex Mills, *Use of Critical Materials in Catalysts for the Petroleum and Chemical Industries, Cobolt and Platinum Group Metals* (prepared for OTA by Inco Research & Development Center, Inc.). Much of the information in this section is derived from this report.

As shown in table 6-5, three major processes dominate cobalt catalyst consumption: petroleum hydroprocessing, used to remove contaminants from sour and heavy crude oil; alcohol production through hydroformulation; and production of terepthalic acids and derivatives, used to produce polyester fibers and films. Cobalt is also used in catalysts to produce synthetic fibers, solvents, pharmaceuticals, and industrial chemicals.

Significant recycling of the cobalt used in chemical catalysts is occurring. According to Inco, about 1.5 million pounds of cobalt were consumed in both chemical and petroleum catalysts in 1982. Of this, 1.1 million pounds—about 72 percent—was contributed through recycling. Fresh cobalt needed to makeup the difference was only about 426,000 pounds. This is less than some other estimates which may underestimate the extent of recycling by the chemical industry.

However, cobalt from spent petroleum hydroprocessing catalysts is not now recycled. Since none is recovered, all of the cobalt consumed in hydroprocessing was fresh cobalt. Inco estimated that about 270,000 pounds of cobalt was consumed in hydroprocessing in 1982. This is less than some estimates for prior years, due to lower refinery utilization. The Inco estimate is consistent with a National Materials Advisory Board finding that between 200,000 to 300,000 pounds of cobalt were consumed in this use in 1982.

Table 6-5.—Cobalt Consumption and Recycling in Catalysts, 1982

Process	Cobalt consumption (thousand pounds)	Percent recycled	New cobalt for makeup (thousand pounds)
Hydroprocessing . .	270	0	270
Hydroformulation . .	700	90	70
Terephthalic acid . .	500	90	50
Organic acid	35	0	35
Alkyl amines	30	95	1.5
Total	1,535	72	426.5

SOURCE: F. J. Hennion, J. J. de Barbadillo, J. H. Weber, and G. Alex Mills, *Use of Critical Metals in Catalysts for the Petroleum and Chemical Industries (Cobalt and Platinum Group Metals)*, 1983. Report prepared for OTA by the Inco Research & Development Center, Inc., December 1983.

Expanded use of hydroprocessing catalysts in the petroleum industry is likely in the years to come. However, growth in demand will probably be less than was anticipated in the mid and late 1970s, when refineries were rapidly installing hydroprocessing capacity to process heavy source crude oils obtained from non-OPEC sources. The combined effects of energy conservation and the 1981-82 recession have resulted in scaling back projected requirements. While hydroprocessing capacity can be expected to grow appreciably from the depressed 1982 levels, "fresh" cobalt requirements will not necessarily increase proportionately. According to the National Materials Advisory Board, future cobalt make up requirements could be in the range of 200,000 to 400,000 pounds a year, assuming that effective recycling takes place. Substitution of nickel-molybdenum catalysts could reduce future requirements by another 100,000 pounds a year, according to NMAB.[36]

In current practice, hydroprocessing catalysts may be regenerated one or more times in the course of their life cycle (2 to 3 years). At some point, however, the catalyst becomes so contaminated that subsequent regeneration is impossible. These spent (unregenerated) catalysts may be stored temporarily on site by refiners, landfilled, or sent to a processor for recovery of non-cobalt metal values or for export. The typical spent catalyst will contain about 8 percent molybdenum, 1.5 percent cobalt, 0.5 to 1.5 percent nickel, 1 to 6 percent vanadium, 10 to 15 percent carbon, 10 percent sulfur, 0.2 percent phosphorus, and the balance, alumina.

During the late 1970s, when molybdenum and cobalt prices were very high, considerable effort was made to recover metal values from these spent catalysts. However, most of these efforts were discontinued as prices fell. By

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[36] *Cobalt Conservation Through Technological Alternatives*, op. cit., p. 119.

1982, Gulf Chemical & Metallurgical Co., of Freeport, TX, was believed to be the only domestic firm recovering metal values from spent hydroprocessing catalysts. Gulf C&M, which has been in the catalyst recycling business for over two decades, uses a combination of pyro- and hydro-metallurgical techniques to recover molybdenum and vanadium values from the spent catalysts but does not currently recover cobalt, nickel, or other metals.

From years of reprocessing, some 100,000 tons of processing residues are reported to have accumulated at the Gulf C&M facility. As much as 7 million to 8 million pounds of cobalt and nickel may be present in this residue, some portion of which could be recovered with adoption of adequate reprocessing technology. The company has reportedly developed a pilot-scale process to recover nickel, cobalt, and alumina values from this residue, but economic recovery of these metal values at current prices is not feasible. Because Gulf C&M reprocesses spent catalysts from both foreign and domestic sources, more cobalt residues are accumulated at the facility each year than are generated from domestic hydroprocessing activities alone.

At least two other domestic firms—Hall Chemical of Wickliffe, OH, and CRI Metals of Baltimore, MD—have announced plans to construct facilities to reclaim cobalt and other metals from spent hydroprocessing catalysts. Hall Chemical, which currently produces 1 million pounds of cobalt salts annually, is constructing a facility (at Arab, AL) said to be able to reclaim individual components of spent cata-

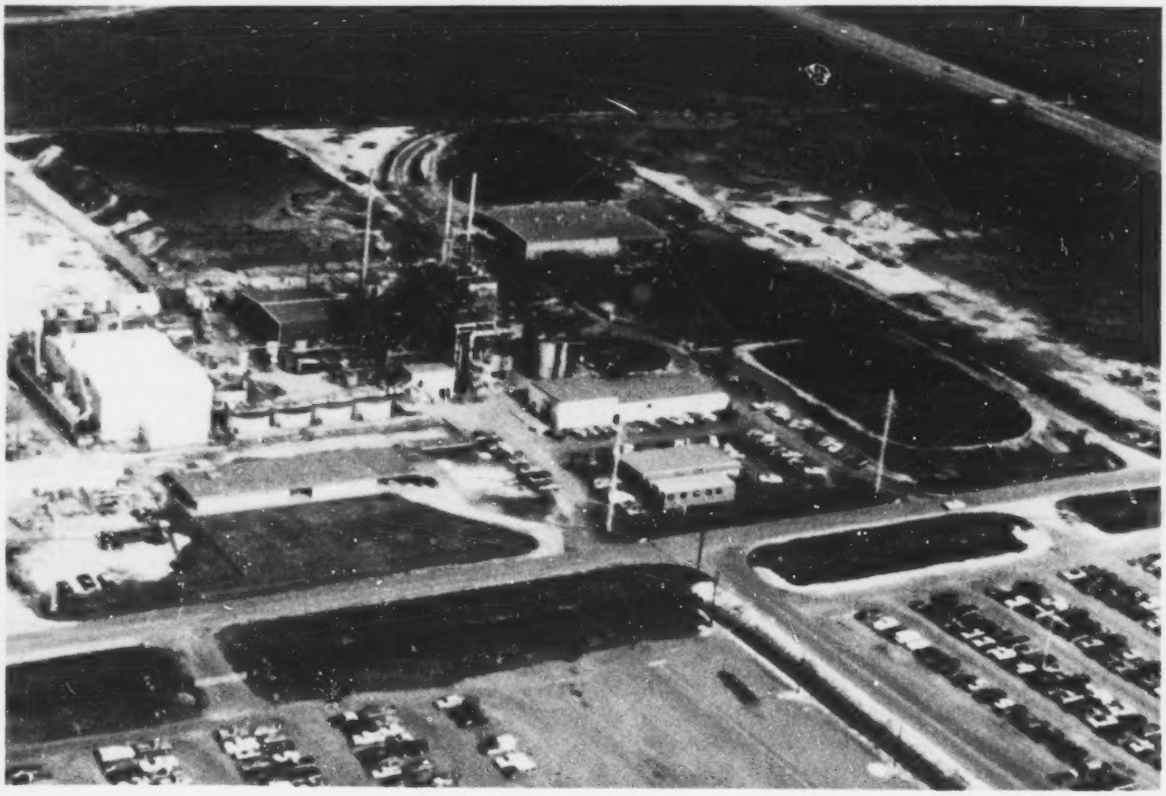

Photo credit: Gulf Chemical & Metallurgical Co.

Molybdenum and vanadium are recovered from petroleum refinery catalysts at this plant in Texas. Several million pounds of potentially recoverable nickel and cobalt are left in the waste and slag that is stored in containment ponds surrounding the plant lysts, including cobalt, nickel, molybdenum, vanadium, sulfur, and alumina. Hall intends to purchase spent catalysts from generators around the world.

CRI Metals, a unit of Catalyst Recovery Inc., has announced plans to establish a hydroprocessing catalyst reclamation facility in the South. The CRI process has been evaluated through pilot plant trials, but CRI has yet to commence construction, owing to depressed metal prices. Like the Hall process, the CRI plan is to recover several contained metals—cobalt, nickel, vanadium and alumina—from the spent catalysts for reuse by the catalyst industry. CRI apparently plans the recycling venture to complement its current catalyst regeneration activities.

Although the industrial capability to reclaim cobalt from spent catalysts may soon be in place, prospects for improved recovery will depend on an increase in cobalt prices. Sizable quantities of spent catalysts may continue to be landfilled, with cobalt values effectively lost in the interim. From the refinery's point of view the fastest method of disposal of spent catalysts is preferred. At current prices, this often means paying the freight to ship spent catalysts to reprocessors, storing the catalyst at a temporary site off the premises, or landfilling. While the technology exists to reclaim landfills, the high cost of such activities means that recovery of cobalt values from landfills is unlikely.

An important issue associated with both recycling or landfilling of spent hydroprocessing catalysts concerns hazardous waste disposal requirements. Although spent hydroprocessing catalysts are not a listed hazardous waste, some spent catalysts may contain trace amounts of lead, arsenic, and other compounds that are toxic. For hazardous wastes, refiners must decide within 90 days about whether the waste is to be landfilled in an approved site or recycled. With current depressed metal prices, there is little economic incentive to recycle these spent catalysts, so that many refiners may choose to landfill them.

Stainless Steel and Steel Process Wastes

Chromium used in stainless steelmaking is obtained from ferrochromium and from scrap. The scrap charge includes home scrap gathered within the plant during various stages of the steelmaking process, prompt scrap obtained from mills and fabricators, and obsolete scrap from postconsumer products and salvage. With the exception of steelmaking wastes, home scrap is generally recycled with a high degree of efficiency. Stainless steel producers routinely recycle most of the solid scrap generated in making stainless steel and in forming primary products, such as sheets, bars, and wires. An estimated 35 to 45 percent of stainless steel production is derived from such home scrap, but since the home scrap cycle is within the mill, it is not considered to be a secondary supply source.

Owing to adoption of the AOD process, which cut losses of chromium to slag by more than half, purchased scrap is an increasingly important source of chromium in stainless steel products. Prompt industrial scrap and obsolete scrap together form the purchased component of scrap supplies. An estimated one-fourth of the chromium needed to make stainless steel and heat-resisting steels in the 1977-81 period came from purchased scrap.[37] Chromium is present in other alloy steels and in cast iron scrap, but in low concentrations that do not favor recycling for chromium content. These materials are usually recycled for their iron content, and the value of the alloying metals is lost (this practice is referred to as "downgrading").

More chromium may be lost each year to downgrading or to failure to recover obsolete products than is recovered from purchased scrap. According to estimates prepared for the Bureau of Mines,[38] about 135,000 tons of stainless steel scrap containing about 24,000 tons of chromium were included in the carbon steel scrap used in nonstainless steelmaking in 1977. Another 38,000 tons of chromium was lost in obsolete scrap that was not recovered. (The range of uncertainty of these estimates is high owing to a variety of factors, including imprecise export and import data and long lifetimes of stainless steel products.) Of course, not all of the stainless steel that was downgraded could have been recovered, since it may have been present only in small amounts or have been inseparable from other materials, but the volume of downgraded scrap makes it clear that there are major opportunities to increase the recovery of chromium from scrap.

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[37] U.S. Department of Commerce, *Critical Materials Requirement of the U.S. Steel Industry* (Washington, DC: U.S. Government Printing Office, 1983), p. 32.

[38] Charles L. Kusik, et al., *Availability of Critical Scrap Metals Containing Chromium in the United States: Wrought Stainless Steel and Heat Resisting Alloys*, U.S. Department of the Interior, Bureau of Mines Information Circular 8822 (Washington, DC: U.S. Government Printing Office, 1980).

Large quantities of scrap are generated when stainless steel is made into fabricated products, but most firms collect and separate the better quality scrap for sale either to scrap collectors or to primary producers for recycling. The comparatively low value of chromium in prompt industrial scrap may slow the return of some scrap for recycling and lead to some downgrading. The nickel-chromium stainless steels (AISI 300 series) are usually recycled because of the high value of nickel and other alloying agents. Recycling of the 400 series scrap, which has 12 to 30 percent chromium but little nickel or other alloying agents, is affected by the relatively low value of chromium.

Recovery of obsolete stainless steel scrap is impeded by dispersed location, the uncertain quality of materials in the scrap, and the long lifetime (5 to 25 years or more) of stainless products. Only a small proportion of stainless steel used in appliances, cutlery, and other consumer items is ever likely to be recovered from scrap, although some may end up in municipal solid waste collection systems from which metals recovery is possible. Fuller recovery of stainless steel scrap from used automobiles, machinery, and other industrial applications takes place, but seldom in excess of 60 percent.

Automobiles provide the single greatest opportunity for reduced downgrading of obsolete chromium scrap. About one-third of the obsolete stainless steel recycled in 1977 came from scrapped automobiles, but this amounted to only about 30 to 40 percent of the potential quantities of chromium that could have been recovered from scrapped cars. Baling, which is used for 10 to 20 percent of scrapped cars, prevents recovery of most stainless steel except easy-to-remove items, such as hubcaps. Shredding of vehicles permits better recovery since nonmagnetic stainless steel can be separated from the carbon steel scrap and sold separately. However, magnetic stainless steel, including the steel used for converter shells, is not easily separated. This downgrading of stainless steel is not likely to be overcome because of the low value of the chromium and the high cost of identifying and separating it from other steels.

Prospects for improved recovery of chromium from scrapped automobiles will be closely tied to efforts to recycle PGMs in catalytic converters, since the converter shells are made of stainless steel. The average 1976 U.S.-built car (now approaching obsolesence) contained about 4.8 pounds of chromium, of which 2.6 pounds was contained in the shell of the catalytic converter. Since 1975, chromium used in catalytic converters has averaged about 10,000 tons per year. Assuming that 70 percent of the cars that annually become obsolete reach dismantling yards, 7,000 tons of chromium could theoretically be recovered from converter shells alone. Since additional losses are likely, recovery of 5,000 to 6,000 tons per year is probably the maximum practical level of recycling. Most cars now manufactured have monolithic-type converters (containing about 1.5 pounds of chromium), so that per vehicle chromium recovery rates in the mid-1990s will decline compared to today. At the same time, the number of cars scrapped each year may grow, hence, the overall amount of chromium that is potentially available for recycling will increase.

The value of chromium in the converter is low, however, and the recovery of the shell for recycling will depend largely on the value of the PGMs contained in the catalyst itself. Most dismantlers—even those who remove the converter to collect PGM catalysts—do not segregate the shell for recycling as stainless steel scrap. Instead, the shell is shredded or baled with the rest of the car.

While small in relation to overall chromium demand, appreciable quantities of chromium as well as other critical metals are also lost in flue dusts, slags, sludges, and other steelmaking and chemical wastes each year. These wastes are not suitable for direct recycling because of contaminants such as lead or zinc, but the chromium and other metals from some of these wastes are increasingly recovered through special processing.

According to Bureau of Mines researchers, about 17,400 tons of chromium were contained in metallurgical wastes generated in 1974 (the most recent year which comprehensive data were collected).[39] Until recently, these low-grade wastes were almost entirely unrecovered. However, some firms are now commercially recovering chromium containing wastes, and several steel producers have established their own in-house waste recovery programs. A partial impetus for this has been environmental regulations restricting the disposal of solid wastes.

Since 1978, Inmetco, a subsidiary of Inco, has been recovering chromium and nickel from low-grade steelmaking wastes. This facility has the capacity to process 47,000 tons of waste per year to produce 25,000 tons of pig metal containing 4,500 tons of chromium and 2,000 tons of nickel. The pig metal, which is 18 percent chromium and 8 percent nickel, is suitable for use in AISI-type 304 stainless steel or, if it contains molybdenum, AISI 316. Inmetco currently processes about 75 to 80 percent of the flue dust, mill scale, and grinding swarf of U.S. stainless steelmakers. The company estimates that 3,100 tons of chromium was contained in wastes entering their plant in 1982, of which 2,800 tons were recovered. The Inmetco facility also has the capacity to recover chromium and other materials from catalysts, superalloys, and other products. An Inmetco subsidiary, Pittsburgh Pacific Processing Corp., reprocesses oil-contaminated scrap.

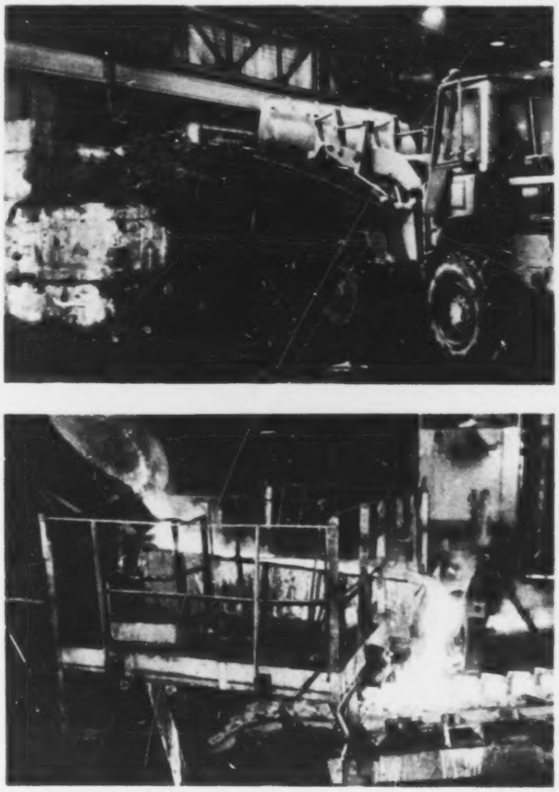

Photo credit: Inmetco

Chromium waste and slag is recycled into chromium-iron ingots at the Inmetco plant in Ellwood, City, PA

Economic processes for recovery of chromium and other metals from specialty steelmaking slags have yet to be developed. Estimates made in the 1970s of nationwide losses of chromium to slag in stainless steelmaking vary widely—from 3,000 to 30,000 tons per year. The lower figure is from the previously cited 1974 estimate of total chromium losses in metallurgical wastes, and appears to be quite low. The latter figure, based on 1965-75 data, is from a study by the National Materials Advisory Board, which also projected that losses would be reduced to about 10,000 to 15,000 tons per year as stainless steelmakers switch entirely to the AOD process.

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[39] W. M. Dressel, L. C. George, and M. M. Fine, "Chromium and Nickel Wastes: A Survey and Approval of Recycling Technologies," *Proceedings of the Fifth Mineral Waste Symposium*, Eugene Aleskin (ed.), cosponsored by the U.S. Bureau of Mines and the IIT Research Institute (Chicago, IL: IIT Research Institute, 1976), p. 269.

Revised estimates do not appear to have been made since the NMAB study, which was published in 1978, but the AOD process is now used almost universally. Nonetheless, the losses remain appreciable. Chromium content in steelmaking slags analyzed by the Bureau of Mines Rolla (MO) Research Center range between 1 and 12 percent, with most samples in the range of 6 to 7 percent. Experiments being conducted at the Center are aimed at upgrading chromium and nickel from crushed and ground slag. Concentrations of more than 20 percent chromium have been achieved. Future research will assess ways to recycle the concentrates in steelmaking furnaces.[40]

Over 3,000 tons of chromium were also lost annually in processing wastes from the chemical industry, metal plating and etching shops, and leather tanning firms, according to the 1974 data mentioned previously. Recovery of the chromium in such wastes is expensive, and until recently wastes were generally disposed of in municipal wastewater systems or landfilled without significant preprocessing. Environmental requirements under Subtitle C of the Resource Conservation and Recovery Act (RCRA) and the Federal Clean Water Act have resulted in the need to process such wastes prior to disposal. As a result, the opportunity to recover chromium from the waste has arisen.

Many metal finishing wastes are classified as hazardous wastes by the Environmental Protection Agency and are subject to the disposal requirements of RCRA. Pollutants, including chromium, must be reduced to acceptable levels before disposal in Subtitle C landfills. Disposal fees at landfills may run on the order of $25 to $50 per drum, which does not include costs of transportation and preprocessing.[41] Recovery of metal values may be incorporated into waste processing, and the value of the metals can then help reduce the cost of disposal.

Several processes have been developed or are under development by public agencies and industry to recover or recycle metals from processing wastes. Corning Glass reportedly has developed a closed-loop process which permits reuse of chromic acid etching solutions, thus reducing the amount of waste and reducing the need for new chromium-bearing chemicals. Another process to recover chromic acid etching solutions, developed by the Bureau of Mines, has been demonstrated to be economically competitive with the purchase of new acid, when savings of disposal costs are included in the analysis. This process, which extends the useful life of the acid a hundred fold, results in major materials savings and also permits the recovery of other metals, such as copper, which can be sold.[42]

Electronic Scrap

The key constraint in recycling of PGMs from electronic scrap is the very small amount of metal used in each unit. The two largest consumers of PGMs in the electrical and electronic sector are the telecommunications industry, which uses them in electromechanical contacts, and the ceramic capacitor industry. In telephone relays, palladium and platinum are found in the contact points, which are brazed to base-metal alloy arms. In a single hand-dismantled relay module taken from a large unit, the Bureau of Mines found 18 large and 36 small PGM contacts, weighing a little more than 0.06 of 1 percent of the weight of the whole module.[43] The National Association of Recycling Industries estimates that 1,000 tons of telephone relay scrap are generated each year. However, this scrap contains only a minute proportion of PGMs.

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[40] As discussed in *Bureau of Mines Research 83*, op. cit., p. 104.

[41] U.S. Environmental Protection Agency, *Environmental Pollution Control Alternatives: Sludge Handling, Dewatering and Disposal Alternatives for the Metal Finishing Industry* (Washington, DC: U.S. Government Printing Office, 1982), p. 1, EPA 62515-82-018.

[42] Deborah A. Spotts, *Economic Evaluation of a Method to Regenerate Waste Chromic Acid-Sulfuric Acid Etchants*, U.S. Department of Interior, Bureau of Mines Information Circular 8931 (Washington, DC: U.S. Government Printing Office, 1983).

[43] Fred Ambrose and B. W. Dumay, Jr., "Mechanical Processing of Electronic Scrap to Recover Precious Metal Bearing Concentrations," paper presented at the International Precious Metals Institute Conference, Vicksburg, VA, May 1983.

Another potential barrier to recycling of PGMs from electronic scrap is the fact that palladium (which, with an average 1982 dealer price of $100 per troy ounce is much lower in price than platinum or gold) predominates in this sector. Palladium is used in ceramic capacitors and is increasingly substituted for gold in low-voltage, low-current electrical contacts, such as telephone relay contacts. Higher reliability electronics, including those for military use, require greater amounts of platinum and gold in contacts, capacitors, and other electronic components.

Despite these potential barriers, there is a growing electronic scrap recycling industry in the United States. An industry observer[44] estimates that 102,000 troy ounces of platinum, or more than the total yearly platinum purchases by the industry, were recovered from electronic scrap in 1982. The growth in recycling of this type of scrap is reflected in the location of the secondary precious metals industry. Twenty years ago, most precious metals refiners and semi-refiners were clustered around the jewelry industry on the east coast. Today, many semi-refiners and refiners are located in California's "Silicon Valley," Texas, and other areas where the electronics industry has developed.

As in other sectors, PGM recovery is greatest from manufacturing scrap. Large refiners such as Johnson Matthey deal in both primary metals and scrap, supplying the electronic component industry with palladium metal, powders, and pastes, and recycling the metal from their reject components. In addition, some large electronics companies have set up their own in-house recycling processes to recapture the precious metals from both their manufacturing scrap and obsolete scrap. However, the percentage of PGMs recycled from obsolete electronic scrap is generally lower. Because of the high labor costs involved in manually processing electronic scrap prior to final refining, some electronics firms and scrap dealers find that foreign dealers offer the best price for their scrap. Material is shipped both to Europe, where such firms as SGM in Belgium have a long history of expertise and sophisticated technology for precious metal refining, and to Taiwan and other Asian countries, where lack of raw materials and low labor costs make low-grade scrap more attractive.

Industry assessments of the quantity of electronic scrap exported by the United States vary. Total sales of PGMs to the electrical and electronic sector were 438,000 troy ounces in 1982. By comparison, exports of all types of PGM-bearing scrap that year were 388,437 troy ounces.[45]

Future trends in domestic recovery of PGMs from electronics are difficult to predict. Over the next decade, the scrap market is expected to increase as technological advances make equipment obsolete. Computer manufacturers, concerned about possible resale of their obsolete components, may crush the parts and sell them for recycling. However, whether the platinum group metals found in this scrap are recovered for U.S. consumption depends on a variety of factors. While some of the materials may be exported for overseas refining, this may be done on a toll-refined basis. For example,

Photo credit: GTE Corp.

Precious metal scrap produced during the manufacture of electronic components is segregated to enhance recycling of gold, silver, and platinum group metals a recently opened Engelhard plant in Cinderford, England, will refine metal from scrapped components and circuitry from U.S. sources on a toll basis, providing an equivalent amount of PGMs to those sources from Engelhard's U.S. refineries.[46] In addition, a number of European firms, such as De Gussa, a German firm, have begun to operate PGM recycling plants in the United States. It is too early to tell whether these trends will have a major impact on the amount of scrap that is exported.

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[44] Mark Stringfellow, "Platinum: Its Present and Future," paper presented to the National Association of Recycling Industries, Dec. 15, 1982.

[45] U.S. Department of Interior, Bureau of Mines, *Mineral Industry Surveys, Platinum Quarterly*, June 7, 1983, table 5.

As in other platinum-consuming industries, the long-term potential for recycling of strategic materials from electronics will depend on the quantities of materials used in production. The rapid evolution of the electronics industry has led to continual improvements in efficiency of use of the precious metals. For example, palladium-silver alloys are increasingly replacing pure palladium in electrical contacts, dampening both palladium use and potential future levels of palladium recycling. In addition, composites show promise for replacing contacts made entirely of PGMs.[47] A fiber composite made of a copper matrix with embedded palladium fibers and an overall palladium content of 30 percent has the same electrical and thermal conductivity as a palladium-copper alloy having a composition of 60 to 85 percent palladium. One of the greatest impacts on PGM use will come from the Bell System's present conversion to solid-state switching, thus reducing electromechanical switching and platinum and palladium demand.

Despite these trends in increased efficiency of use, opposing trends are causing overall demand for PGMs in electrical and electronic equipment to increase. Because of its low cost, palladium is increasingly being substituted for gold in electrical contacts and printed circuits, and new types of components, such as ceramic capacitors, are making use of PGMs. In addition, ruthenium, which is already used in the large quantities of reed switches used in electronics, is finding new applications in the industry. Overall, it appears that consumption of palladium and ruthenium will increase, and that there will be large quantities of these materials available for recycling beyond 1990.

Technologies for recycling PGMs from electronic scrap require further development. While several hydrometallurgical and pyrometallurgical processes are available for final refining of PGMs, preprocessing technology is not yet adequate. Currently, there are numerous steps in the refining process, often carried out by different companies, with each step adding to recycling costs. The initial manual disassembly of the most valuable components from the aluminum and copper frames (e.g., snipping off contacts with wire cutters) may be done either by the electronics company or by a specialized preprocessing firm. These firms sell some components for reuse and others for scrap to both domestic and foreign businesses.

Semi-refiners of electronic scrap collect circuit board scrap after initial disassembly and process it further. This may involve simply stripping off the plastics with chemicals, followed by shredding and chopping the components, or more complex steps such as ball mill crushing and pulverizing of capacitors, which leave a "sweep" or pulp containing precious metals. Other firms combine these processing steps with smelting out the PGMs as crude bullion, which may be either sold to electronic component manufacturers or shipped to refiners. Final refining to high specifications is generally done by one of a handful of specialized refiners using pyrometallurgical techniques.

Using obsolete electronic scrap provided by the Defense Property Disposal Service, the Bureau of Mines has developed a process for mechanically upgrading electronic scrap. The process is made up of a series of unit operations using technology already widely available in the recycling industry. These operations include shredding, eddy current separation, and high-tension separation. The process can break down mixed scrap into an iron-base fraction, an aluminum base fraction, a wire fraction, and a high and a low precious metal concentrate, greatly reducing the amount of material that must be processed for precious metal recovery and also reducing shipping and toll refining costs.

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[46] Judith Crown, "Engelhard Revamping Precious Scrap Setups," *American Metals Market*, July 8, 1983, p. 1.

[47] Stockel, "Composites for Electrical Contact Applications," *Zeitschrift fuer Werkstoffechnik*, July 1979.

The Bureau of Mines process could reduce costs of refining electronic scrap by replacing costly, slow, and unpredictable hand stripping with reliable automated techniques. While it can be used on mixed scrap, it is most effective when incoming scrap is first separated into lots. For example, connector assembly plating, printed circuit cards, wiring, and other components high in precious metals should still be manually separated from their outer box covers. While all segments of the precious metals recycling industry have expressed interest in the process, economic factors may prevent widespread adoption of fully automated processing. Some in the recycling industry view the high capital costs of the equipment and the high energy costs of operating it as formidable barriers to profitable domestic processing of low-grade mixed scrap.

Cemented Carbides

About 8 percent of the cobalt consumed domestically each year is used as a binder in cemented carbides, which are used in cutting tools or other high-wear applications. Most scrap produced during fabrication of cemented carbides is now recovered, and in the last few years, producers of cemented carbides have begun to recycle substantial quantities of obsolete cemented carbide scrap. This improved recovery became pronounced in the late 1970s but the improvement was less a function of industry response to the cobalt price increase than of the ongoing adoption of technological advances by tungsten carbide producers.

According to the NMAB, up to 0.5 million pounds of cobalt from obsolete products are now recovered by tungsten carbide producers each year. In early 1984, installed capacity to reprocess such scrap is estimated to be 36 percent of domestic consumption. Obstacles to increased recycling of obsolete carbide scrap include widespread geographic diffusion of products and difficulties in recovering worn or broken parts.

Tungsten carbide scraps constitute a major proportion of current tungsten recycling. GTE Corp., the largest domestic producer of tungsten, established a patented process in the early 1970s for recycling tungsten scraps and in 1978, a proprietary process for producing extra-fine, highly purified cobalt powder from recycled scrap on a toll and nontoll basis. With sintering, the powder can be turned into a metallurgical cobalt material suitable for use in superalloys. GTE has also established a pilot plant project to reclaim cobalt from superalloy scrap. The recycled cobalt is equivalent to highly refined cobalt produced from virgin ores. Although the cobalt is produced as powder for cemented carbide use, it may be suitable for superalloys if compacted and pelletized.[48]

Other cemented carbide producers, such as Teledyne, employ a zinc process to recover both cobalt and tungsten carbide as powders from tungsten carbide scrap. The process was developed by a British firm in 1946 and furthered by the U.S. Bureau of Mines.

Prospects for Conservation of Strategic Materials

Table 6-6 summarizes key opportunities for increased recycling of chromium, cobalt, and PGMs. Data limitations prevent close estimation of prospective recovery opportunities in many applications, but it is clear that very large quantities of materials are involved. Under tight supply conditions, appreciable increases in recycling can be anticipated as scrap collectors, processors, and consumers respond to increased prices of primary metals.

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[48] Information provided to OTA by GTE, Aug. 10, 1983.

Table 6-6.—Selected Opportunities for Increased Recycling of Chromium, Cobalt, and Platinum Group Metals

Current level of recycling	Key recovery opportunities	Barriers to increased recycling		
		Technical	Economic	Institutional
Superalloys (Co, Cr):				
An estimated 2.8 million lbs of cobalt-bearing superalloy processing scrap was lost or downgraded in 1980; 1.2 million lbs of cobalt in obsolete scrap was not recovered. However, these figures are based on 1976 scrap use rates.	Increased recovery of obsolete scrap, reduced downgrading of high-quality industrial scrap and recovery of wastes, using advanced recycling technologies.	Concern about contaminants limits recycling in superalloy production to high-quality scrap and processes that have been certified. Experimental processes to reclaim elements separately have not been commercialized.	Current prices encourage downgrading of superalloy scrap for use in stainless steel or nickel alloy production in which the cobalt is not needed. Certifying recycled materials for superalloy use is expensive and time-consuming.	Not significant once manufacturing specifications for use of recycled materials have been established; however, this can take several years.
Petroleum hydroprocessing catalysts (Co):				
No cobalt recovery at this time; 270,000 lbs of cobalt was not recovered from spent catalysts in 1982.	Cobalt consumption in catalysts is expected to grow to 675,000 lbs in 1990, 90% of which could be recovered.	Not significant; various proprietary processes are purported to recover Cr, Co, Ni, Mo, Va, and other metals for catalytic or chemical purposes.	Current prices may discourage recovery of cobalt in preference for molybdenum. However, at least two firms have proprietary processes for recovery of all elements in catalysts.	Landfilling of spent catalysts by refineries prevents possible future recovery of some catalysts.
	Accumulated spent catalyst residues may include 8 million lbs of cobalt and nickel.	Some technical problems; pilot-scale recovery process is under investigation by a private firm.	Reprocessing of residue is not profitable at current prices.	Not significant; residues are stored on site of major processor.
Cemented carbides (Co):				
10 to 30% of cobalt used in domestic cemented carbide shipments came from recycling.	Obsolete scrap (a high proportion of industrial scrap is already recovered.)	Not significant: several firms use a Bureau of Mines process to recover cobalt binders. One firm produces highly refined, pure cobalt powders from scrap that could potentially be used in other premium uses.	Recovery of obsolete scrap from dispersed uses may not be economic at current prices.	Lack of effective scrap collection programs by industrial users. Practical limits for postconsumer recovery vary by industry. However, some users (such as the oil industry) return 80% of their scrap for recycling; the coal mining industry, by contrast, only returns 15% (out of a practical limit of 50%).

Table 6-6.—Selected Opportunities for Increased Recycling of Chromium, Cobalt, and Platinum Group Metals (Continued)

Current level of recycling	Key recovery opportunities	Barriers to increased recycling		
		Technical	Economic	Institutional
Stainless steel (Cr):				
Home scrap is efficiently recovered; purchased scrap for stainless steel accounted for about 20% of total demand for Cr in 1983.	Improved recovery, reduced downgrading of obsolete scrap, especially automotive catalytic converters.	Not significant, but current industrial practices encourage downgrading.	Comparatively low price of chromium and labor costs associated with removal of stainless steel components from automotive and other obsolete scrap encourages downgrading.	Recovery of obsolete consumer products containing stainless steel catalytic converter shells is a primary candidate for recovery, but will depend on effective linkage of PGM and Cr recovery efforts.
	Increased recycling of industrial processing wastes (slags, flue dust, low-quality fabrication scrap, etc.)	Recovery of chromium from some wastes (e.g., slags) is technically difficult.	Resource recovery from industrial wastes may not be economic; however, commercial recovery of low-grade flue dusts, grindings, turnings, borings is now being undertaken commercially.	Environment and solid waste disposal requirements are providing increased impetus to recovery where economic.
Catalytic converters (PGM, Cr):				
Up to 30% of scrapped converters may now be recovered for recycling.	Retrieval of PGM from scrapped automobiles, muffler shops, etc. Maximum theoretical PGM recovery will grow to 800,000 troy oz by 1995. Maximum practical recovery rate will probably be about 500,000 troy oz.	Several companies have proprietary processes to recycle catalysts.	Dependent on PGM prices, but appears favorable.	Some dismantlers do not remove catalytic converter from cars prior to scrapping. Collection networks have not been established in many areas. Dismantlers want more for the catalysts than reclaimers are willing to pay.
Electronic scrap (PGM):				
High for industrial scrap, low for obsolete scrap.	Obsolete scrap.	Lack of technology for preprocessing of scrap to a form usable by a refinery.	Depends on PGM prices; hand labor disassembly encourages export of scrap.	Collection of obsolete scrap from consumer electronics (i.e., households) is unlikely without incentives. Value of scrap is not widely recognized; monitoring of trends is inadequate.

SOURCE: Office of Technology Assessment.

Evidence from past "crises"—most notably the Canadian nickel strike of 1969 and the cobalt price spike in 1978—suggests that U.S. industry can quickly increase recycling when concerns about supplies are paramount or when prices rise rapidly. In 1969, nickel scrap purchases exceeded 1968 levels by over 60 percent despite the fact that the Canadian strike did not occur until mid-1969. Nickel scrap as a proportion of domestic consumption expanded rapidly over the following 3 years—accounting for 22 percent of domestic supplies in 1972 as compared to 8 percent in 1968. (The current level is about 23 percent.) Cobalt scrap purchases doubled in 1978 and remained at or above 1 million pounds per year through 1981, a growth from 4 percent of domestic consumption to 8 percent.

It is more difficult to quantify savings of strategic materials likely to arise from adoption of new manufacturing and processing technologies by U.S. industry, but they are also large—particularly in the cases of manganese used in steelmaking and strategic materials used in superalloys. Upgrading of basic steelmaking processes could lead to important reductions in the amount of manganese needed to produce each ton of steel (see table 6-6). Use of advanced manufacturing technologies by the aerospace industry will reduce chromium, cobalt, and other strategic material input requirements for superalloys on a perpart basis. Part life extension programs could also conserve materials over the long run. As discussed in chapter 7, increased use of coatings and other surface treatment technologies and use of advanced ceramic and composite materials also could reduce per part strategic material requirements, especially in the long term.

Recycling Technology

With some notable exceptions, there appear to be few significant technological barriers to increased recycling of strategic materials. High-quality scrap generated in the production and manufacture of products is recognized to be a valuable source of raw materials by industry and is usually effectively recovered and reused. Ongoing industrial trends, including establishment of specialized scrap processing firms and improved industrial waste treatment processes, have expanded the range of waste materials considered suitable for recycling, so that continued incremental improvement in recycling is likely in the coming decade. Difficulties in identifying and sorting complex scrap containing several materials have recently been eased by the commercial availability of portable and relatively inexpensive instruments suitable for use in scrapyards, as discussed in box 6-A.

In the area of superalloy recycling, considerable technological advances have been made over the last decade. However, additional innovations may be needed if full use of obsolete scrap and other less preferred scrap is to occur. In the most demanding applications, even small trace amounts of inpurities may be unacceptable. Because of concern that contaminants acquired from scrap material could result in failure of superalloy parts, use of superalloy scrap in jet engines has been limited to scrap of the highest quality—generally, home and prompt industrial scrap, although limited use has been made of obsolete scrap obtained from commercial aircraft, where parts can be identified by alloy type. Much of the remaining scrap is downgraded to use in stainless steel, where it is used for its nickel and chromium content. When this occurs, cobalt is lost, and the previously high-quality chromium used in superalloys becomes a replacement for chromium usually supplied from high-carbon ferrochrome or stainless steel scrap.

Nontechnical Impediments

In most applications, institutional and economic constraints on recycling are more formidable than the technical constraints. Fluctuating commodity prices, costs associated with segregation and processing of scrap, transportation costs, and industry structure all affect the ability of recycled materials to compete with primary metals.

ECONOMICS OF RECYCLING AND CONSERVATION

The economic incentive for recycling high-priced materials, such as PGMs, is very high.

However, other strategic metals are less expensive and often account for only a very small proportion of the scrap. For many applications, raw materials comprise only a small fraction of the total value of the product. A 6,000-pound jet engine, for example, may cost $3.5 million, while the value of the materials it contains is only $60,000. Even though an alloy may contain metals that are relatively rare and high priced, the cost of separation of the alloy into its constituents may be so high that it discourages any attempt to recover the metals; so, the alloy is downgraded to recover its nickel and chromium content.

Recycling opportunities will change along with changes in manufacturing processes and product designs. More efficient manufacturing processes will require less raw material, so there will be less prompt industrial scrap available for recycling. New product designs that use combinations of materials to achieve desirable properties will present difficult and expensive problems for the separation of materials for recycling. Often, products can be designed for ease of recycling, but since raw material costs are generally a small component of overall cost, this is seldom done.

Materials conservation is an important side benefit of the advanced manufacturing technologies widely used by the aerospace industry. These technologies may gradually filter down to other industrial users. Diffusion of computer-aided design and nondestructive evaluation techniques may be impeded to some extent by lack of experience of engineers, designers, and others with these new approaches. This is not a major problem in the aerospace industry or in other critical uses, however.

INFRASTRUCTURE

The complex structure of recycling industries, often entailing primary metals processors, collectors and dealers, scrap processors, and parts manufacturers, can inhibit initiation of recycling programs, even when the programs may be economically advantageous. Generally, the secondary metals industry comprises a large number of small firms that respond to prices offered by the primary metals industry. This system works well for materials for which there is a relatively constant demand for a standard product. Although recycling firms can respond rapidly to changes in materials demand due to shortages of primary materials, exacting standards for superalloys and other premium materials can only be met through the use of sophisticated equipment and experienced personnel who are familiar with the needs of consumers. This can delay recycling response time in a shortage situation.

Recycling and Conservation Data Base

Accurate information is needed to have a realistic picture of the potential for recycling to reduce U.S. materials import vulnerability. The existing data are weak, with many uncertainties about their accuracy. Key areas where improvements can be made are: upgrading of annual information about scrap purchases by consuming industries, development and use of materials flow models on a periodic basis, and improved tracking of the ultimate disposition of obsolete scrap and industrial wastes that contain appreciable amounts of strategic materials.

The U.S. Bureau of Mines prepares annual estimates of scrap purchases by domestic industry. In most instances, these estimates are based on voluntary reporting by private firms. Not all firms are canvassed, and of those that are, not all respond. Consumers of more than one strategic material may be surveyed about only one material. Although adjustments can be made to compensate for incomplete reporting, the resulting estimates are subject to considerable uncertainty. In the course of this study, OTA found evidence that substantially more recycling may be taking place than is currently reported in Bureau of Mines' data.[49]

Scrap purchases alone provide only a limited picture of recycling trends. Substantial recycling occurs internally and through toll refining arrangements that do not involve purchases.

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[49] Other reports have reached a similar conclusion. See, for example, the NMAB report, *Cobalt Conservation Through Technological Alternatives*, op. cit., p. 25.

Also, scrap purchases provide no insight into the ultimate fate of scrap that is not recovered. Periodically, Federal agencies such as the Bureau of Mines and the NMAB have published detailed and relatively comprehensive materials flow models for individual metals. These models have appreciably increased understanding of overall recycling trends, but they have been prepared infrequently and there has been little or no consistency in procedures used in developing the models.

A notable impediment—from the perspective of identifying possible responses to disruptions in materials supply—is the absence of information about accumulations of unrecovered obsolete scrap containing strategic materials. Only a portion of the scrap that becomes obsolete each year is recycled domestically. Some is exported, while the rest is unaccounted for in national statistics. Much of this lost material may now be effectively unrecoverable owing to disposal in landfills, dissipative corrosion, contamination, or abandonment in unknown locations. Some, however, may be retrievable from industrial disposal sites, commercial scrap yards, and military storage depots for use during supply disruptions. Extensive efforts have been made over the years to estimate the accumulated "inventory" of potentially recoverable ferrous scrap, but a similar effort to monitor the disposition of strategic materials in obsolete superalloy parts, catalysts, and other applications has not been made. As a result, plausible estimates of the above-ground mine of strategic materials recoverable in an emergency are not available.

CHAPTER 7

Substitution Alternatives for Strategic Materials

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CHAPTER 7

Substitution Alternatives for Strategic Materials

Roles of Substitution in Materials Use

Designers choose materials that they think offer the most attractive combination of service performance and reliability, ease in processing and manufacturing, cost, and availability. However, these factors constantly change as new materials with better properties are developed, better information about existing materials becomes available, new processing techniques are developed, and relative costs and availability of materials fluctuate. Substitution, the process of revising the match between materials and applications, is the material users' technical response to this shifting environment. In some cases, substitution involves finding or developing the best material for the application (replacement); in others, it involves designing or redesigning the application to make the best use of available materials.

Substitutions can be very costly and therefore are undertaken only when there is a high degree of certainty that the benefits will be substantial. To be adopted, a substitute material or design must demonstrate both technical and economic feasibility and must overcome a variety of institutional hurdles. More important, it must gain the acceptance of the designers and end users who will ultimately use it.

Even though substitution includes both replacement and redesign, current strategic materials-motivated substitution research is, for the most part, oriented toward development of alternative materials that have less strategic material content.[1] At present, considerable research—most of it government sponsored—is focused on development of replacement materials that could reduce strategic material requirements in several critical applications. These include, among others, several lower chromium alternatives for existing stainless steels now used in powerplants, chemical processing facilities, and other applications where corrosion resistance in a range of environments is needed; low- or no-chromium alloy steels for bearings, gears, shafts and other high-stress, long-service life applications; and low- or no-cobalt superalloys for gas turbine applications. Some examples of substitutions that have been or could be important to strategic materials use are shown in table 7-1.

Table 7-1.—Examples of Substitution Relevant to Strategic Materials

Direct material substitution:
- Ceramic magnets for aluminum-nickel-cobalt magnets
- Dolomite for magnesia-chromite refractories
- Interchangeability of platinum-group metals and gold in electronic components
- Modified 9% chromium-1% molybdenum steel for 18% chromium-8% nickel stainless steel in reactor vessels, heat exchangers, and tubing in powerplants
- Polymeric materials for decorative chrome in automobiles
- Cobalt-free superalloy for 56% cobalt superalloy in JT-9 jet engine

Process design substitution:
- AOD vessel for double-slag in stainless steelmaking
- Precision casting and forging for machining in parts manufacture
- Continuous casting for ingot casting in steelmaking

Product design substitution:
- Ceramics in experimental automotive gas turbine engines
- Downsizing of turbine engines made possible through the use of lighter materials in aircraft components

SOURCE: Office of Technology Assessment.

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[1] Though product design and redesign can be used to reduce strategic materials requirements, this strategy is less amenable to a centralized research effort because of the vast number of products (and the case-by-case nature of this technique). New manufacturing process designs can also reduce strategic materials needs in some applications. However, these savings are rarely the primary motivation for process development or implementation and are not realized if greater cost or performance advantages lie with other processes. As a national strategy to reduce U.S. dependency on imported materials, product or process design modification can only be successful if design engineers can be convinced to include strategic materials savings as an important objective in design decisions.

Substitution as an Emergency Response to a Supply Problem

To a certain extent, already developed, on-the-shelf substitute materials and technologies can be relied upon in an emergency to conserve materials that are in short supply. As discussed in chapter 3, substitutes for strategic materials in many applications are often available, though not necessarily readily recognizable as such. Alternative materials could be used in these applications with low (or at least tolerable) penalties in performance and cost. The material saved through these measures would then be available for use in critical applications where higher or unacceptable penalties are associated with substitution.

The existence of technically and economically viable substitutes is not the only requirement for a timely response to a supply emergency. For many critical applications, a new material must be tested and its use in a particular component must be qualified (accepted by the consumer) and certified (shown by the producer to meet the consumer's requirements). Thus, immediate response is limited to those materials that are already in (or very close to) commercial use, and to applications that do not have stringent materials requirements or for which the material has been certified and qualified. The substitution response by U.S. industry to prior supply problems involving strategic materials is discussed in chapter 4.

The current ability of U.S. industry to respond to a supply problem with substitution is not known with any degree of certainty. Although a large backlog of alternative materials and technologies is generally conceded to exist, information about many of these potential substitutes has not been assembled in a systematic way which would be accessible to designers, material users, and decisionmakers in an emergency. Development of a substitution data bank or a materials information system that would bring available substitutes to the attention of engineers and designers is one frequently proposed means for reducing U.S. vulnerability to an import curtailment. This concept is discussed further in chapter 8.

Substitution as a Continuing Strategy for Reducing Import Vulnerability

Besides being an emergency response, substitution can also play a key role in long-term strategies to reduce dependency on imported materials. During the last decade, there has been much research focused on development of substitute materials that could reduce strategic material requirements for many alloys currently used in key applications. Other research has been aimed at development and commercialization of advanced materials (e.g., ceramics and composites) which may displace use of strategic materials in some applications.

Although many technically promising substitutes are under development, the extent to which they will be adopted by U.S. industry is difficult to foresee. In the absence of an immediate availability problem, industry's adoption of new materials, designs, and manufacturing technologies is usually not motivated by concerns about strategic materials availability. Generally, the new technologies will be used only if they offer some more immediate benefit such as reduced costs, increased outputs, improved product performance, or potential new products.

A successful long-term strategy for reducing U.S. vulnerability to imported materials through substitution depends not only on the technical feasibility of alternative materials but on acceptance of them as practical alternatives by industry. Acceptance comes only when the technical and/or economic benefits have been clearly demonstrated, various institutional barriers have been surmounted, and a high degree of designer and end-user confidence has been established.

Factors Affecting the Viability of Substitution

Technical Factors

Over time, a backlog of proven, on-the-shelf materials and technologies have been developed that for one reason or another have not been adopted by industry. Research and development (R&D) efforts by public and private agencies throughout the world are adding to this store of potential substitutes almost daily. Only a few of these are likely to be adopted by industry at any given time.

Technological barriers to strategic materials substitution can be time-consuming and formidable, especially for applications in which little or no compromise in performance is acceptable. Even when a promising substitute is developed in the laboratory, new and significant technical problems may be encountered when large-scale tests are undertaken to verify laboratory findings. Often, a return to basic research is required to overcome these scale-up problems. Additional technical problems may be encountered when full-scale industrial production is begun.

Economic Factors

The technical potential of substitution to reduce strategic materials requirements is far greater than what is economically feasible. Industry will not adopt technically promising alternative materials unless they are cost-effective compared with current materials. Often, the cost effectiveness of using the current material is not greatly affected by price increases in strategic raw materials. In fact, the prices of raw materials can be such a small part of the cost picture that they are relatively unimportant in a substitution decision. For example, raw materials account for only about 1 percent of the cost of a jet engine. Even platinum group metals (PGMs), which cost between $100 and $400 per troy ounce, account for less than 5 percent of the cost of products manufactured with PGM catalysts. Therefore, all else being equal, a change in the cost of raw materials often has to be dramatic to warrant the expense of shifting to a substitute material. Adoption of a new material may require costly new equipment or changes in operations. There are also costs associated with change itself—for training workers in the use of a new material or process, for changing the design of products, and for adjusting manufacturing practices.

Institutional Factors

An alternative material may take a decade or more to bring to commercial fruition, even after the technical and economic feasibility of the substitute has been demonstrated. Government, industry, academia, professional societies, and standard-setting organizations may all play roles in this process, depending on the material and its application.

Substitution R&D relevant to strategic materials is conducted in government, industrial, and academic laboratories. Since most of the support for this work has come from the government, funding of the projects is subject to shifting governmental budgetary priorities and may not be sustained for the protracted period needed to adequately demonstrate the technical potential of a material or its application. Also, government conducted or sponsored R&D can suffer from insufficient industrial interest in commercializing a material.

Industry, the group which ultimately decides whether or not substitutes are adopted, usually does not commit the funds, time, and effort necessary to develop and qualify substitutes for strategic materials unless such activities also provide cost or performance advantages. Private firms often do not perceive national materials availability and vulnerability as problems that they have a major role in remedying. Availability concerns are usually not immediate enough to cause much corporate concern. Table 7-2 illustrates the representative R&D priorities by government and industry.

Standard-setting and professional organizations play key institutional roles in the development process by testing new materials and developing standards for their use. Often, test-

Table 7-2.—Primary Motivations for Substitution R&D

	Industry	Government
Reduced import dependency		x
Cost advantage	x	
Better performance	x	
New market penetration	x	
Materials conservation		x
Maintenance of national industrial competitiveness		x

SOURCE: Office of Technology Assessment.

ing and standard-setting are done by volunteers from professional societies, with limited resources and time to dedicate to the effort. In other instances, such as the qualification of a new superalloy for jet engine use, testing and qualification is undertaken by an individual firm on a proprietary basis. The effort may have to be duplicated by others if the material is to be used broadly. In many cases, several years of effort—and millions of dollars—may be entailed in testing and qualifying a new material for use in a critical application.

Designer and End-User Acceptance

Acceptance by designers and end users can be the highest hurdle in the adoption of a substitute. These groups sometimes have been indifferent to the need to save strategic materials. A heightened awareness of the importance of design to strategic materials vulnerability may be able to reverse this indifference.

Substitutes are adopted only when component designers and end users have acquired a high degree of confidence in the technical capabilities and economic potential of the new technologies. These materials users will not use any substitute technology with which they are uncomfortable; they are reluctant to make changes, especially if the new designs or replacement materials are relatively untried. Substitution in critical applications often requires a degree of confidence or comfort with the new material or design that can only come from a proven track record. Consequently, promising substitutes are often introduced first into noncritical applications where confidence can be gained without fear of catastrophic failures.

These acceptance hurdles can be especially high for advanced materials. Since many advanced materials are relatively recent developments, they are still fighting to establish a track record. This situation is exacerbated by the fact that most designers receive little formal training in the use of advanced materials.

Summary of Substitution Prospects

On-the-shelf substitutes, which could be adopted by industry relatively quickly, enhance U.S. preparedness to deal with import problems. It has been estimated, for example, that immediately available substitutes could replace one-third of the chromium now used. There are also fully developed substitutes for cobalt and PGM in some applications. Substitution prospects for manganese are less promising, although substantial reductions in the amount of manganese needed per ton of steel produced are likely in the coming years because of the upgrading of steelmaking processes, as discussed in chapter 6.

Industry response time depends in part on the ready availability of information about substitute materials. Technologically sophisticated firms are generally aware of available substitutes, and some are reported to have undertaken contingency planning to address future supply availability problems. Less sophisticated firms may have greater difficulties in obtaining such information in the event of an actual supply disruption, and, as a general rule, would have the greatest difficulty in competing for scarce materials.

Substitution prospects in many critical economic and defense applications depends partly on overcoming significant technical barriers. In these applications, substitutes must equal the performance of the materials already used, which is often technically difficult. Substitutes with low strategic material content have not yet been developed for some of these important applications. The degree of commitment needed to develop direct substitutes is substantial in both money and time. For applications which require that alternative materials be qualified, the development effort may take 10 or more years and several million dollars, even after their technical promise has been identified in the laboratory.

Industry has little incentive to develop substitutes on its own unless clear benefits in cost or performance are anticipated. As a result, the Federal Government has undertaken or sponsored most of the research where strategic materials savings, not cost or performance benefits, are given top priority. Several Federal agencies, including the Department of Energy (DOE), the Interior Department's Bureau of Mines, and NASA have sponsored research programs aimed at developing substitutes for strategic materials. However, the sustained support needed to develop particular materials to the point of commercialization generally has been lacking.

Substitution research programs undertaken by NASA, the Bureau of Mines, and DOE national laboratories have resulted in lower chromium research alloys that are potential substitutes for stainless steel in some applications. (Selected examples of these alloys are discussed in a subsequent section, and summarized in table 7-4.) Even if fully developed, most of these materials would not duplicate the great versatility of the high-volume stainless steels and would be capable of replacing stainless steels in only a limited range of applications.

With some exceptions, these substitutes are only in the initial stages of development. In most instances, a continuing government commitment will be required if these materials are to be fully developed, since private industry is unlikely to undertake this research itself. Issues surrounding possible additional Federal support for such development activities are discussed in chapter 8.

The Federal Government—especially NASA, through its Conservation of Strategic Aerospace Materials Program (COSAM)—has also sponsored initial laboratory work on replacement superalloys that have reduced levels of cobalt. These research materials could potentially reduce the cobalt now used in some nickel-based superalloys by one-half or more. However, full development of these replacement materials would require several more years and millions of dollars in additional funds. As with lower chromium stainless steel, subsequent development steps needed to bring these substitute superalloys to the point of commercial use probably will need to be federally supported if this development is to occur at all.

The changing material requirements of the aerospace industry may make it impractical to develop these direct substitutes for superalloys to the point of commercial use. The development steps required could entail 5 to 10 years of additional effort. Beginning in the mid-1990s, advanced superalloy materials may begin to be commercially used in the next generation of military aircraft. The direct substitutes now under development for currently used materials will not be suitable replacements for new materials used in the next generation of jet engines. (Less near- and medium-term change in materials is expected in the case of stainless steel.) Superalloy substitution research is discussed in greater detail in a subsequent section.

In addition to direct substitutes, advanced materials (including ceramics and composites) are also under development because their properties offer new possibilities in product design and performance. These materials, which contain little or no strategic metals, may have long-term implications for reducing import dependency, although to what extent is not clear. Because the emphasis is on cost and performance benefits, much of the development of advanced materials is carried out by private concerns.

Advanced ceramic materials have the potential to displace metals where exceptional wear-resistance or heat-resistance is required. Current and prospective advanced ceramic applications in which strategic materials are now used are discussed in a subsequent section, and summmarized in table 7-11. Aerospace and automotive applications command most of the funds for ceramic R&D efforts.

Composites (including polymer matrix, metal matrix, and carbon/carbon materials) are primarily under development because of their lightness compared to conventional materials. In critical applications, their potential role in reducing strategic material requirements is likely to be indirect and will depend upon design factors. At present, commercial applications for advanced composites are dominated by aerospace applications and high-value sporting goods. Increased use of composites in automotive applications is predicted.

Strategic materials conservation is not a primary motivation in the development of advanced materials, and the potential of these materials for displacing current requirements for strategic materials should not be overemphasized. Nonetheless, in the long term, they may well bring fundamental changes in the overall mix of materials in the domestic and international economy. Major industrial countries including the United States, Japan, Great Britain, and several Western European countries are all vying for prospective markets for these materials. Moreover, because of their key importance in defense applications, the question of the adequacy of domestic processing capabilities with respect to these materials is likely to be an increasingly important issue. Processing capacity is often located in several different countries. The United States, for example, currently imports from Japan most of its high-quality polyacrylonitrile (PAN) used as a precursor in carbon-carbon composites. The international nature of these markets could create a new type of materials import dependency.

Prospects for Direct Substitution in Key Applications

Adequate substitutes exist for many applications in which strategic materials are now used. For example, aluminum alloys, plastics, and plated carbon steels already compete with stainless steels for many construction and consumer markets. In the event of a chromium supply disruption, these alternative materials would be readily available as substitutes for stainless steel in many nonessential applications where exceptional corrosion resistance is not needed. Similarly, if the supplies of PGM were to tighten, electronic components manufacturers could quickly substitute gold for much of the platinum and palladium now used for contacts. This is a case where raw materials prices are a significant part of the total product cost and can be counted on to drive substitution. Fifteen years ago, gold was the preferred material for contacts, but current prices favor platinum and palladium.

Materials substitution in many essential economic and defense uses is more difficult, however. Performance compromises are very costly in these cases, so the replacement must match or better the properties of the current material. There are very few, if any, immediately available replacement materials capable of meeting the demanding performance standards required for these applications. In some cases, adequate substitutes for the current materials have yet to be developed. In other cases, technically acceptable substitutes may be known, but are too expensive to be used. In still other cases, potential substitutes have been developed in the laboratory but have yet to be taken through the time-consuming and expensive testing processes necessary to make them acceptable for commercial use. Depending on the extent of the laboratory research and the promise shown by the results, some of these substitutes could be brought to the point of commercialization in the next 5 to 10 years, while others are unlikely to be developed fully.

Chromium Substitution in Stainless Steel

Stainless steel accounts for almost half of the total U.S. chromium demand, and about 70 percent of the chromium consumption in metallurgical uses. Table 7-3 shows the contribution of the highest volume stainless steel grades to chromium use. The most common grade, AISI 304, alone accounts for over 40 percent of domestic stainless steel production and over 20 percent of total domestic chromium consumption. Although the chromium content of stainless steels varies from 10 to over 30 percent, on the average stainless steels contain about 17 percent chromium.

The primary function of chromium in stainless steel is to provide corrosion and oxidation resistance.[2] Chromium makes stainless steel highly resistant to damage in a large variety of environments. This characteristic, along with good fabricability and mechanical properties, is what makes stainless steel so attractive for a wide variety of applications, ranging from decorative trim, kitchen utensils, and other consumer products to industrial applications such as tubing and reaction vessels in powerplants and chemical processing facilities.

There is little chance that a universal substitute for stainless steel can be found for use in all of these applications. However, some opportunities exist for piecemeal substitution. The potential for reduced use of stainless steel (and thus chromium) in an emergency is very great in the decorative and consumer uses and low-temperature (room temperature to 900° F) industrial applications. Materials such as aluminum, titanium, plastics, and low-chromium stainless steels (9 to 12 percent chromium) can often substitute without serious performance compromises for stainless steels in these relatively undemanding uses. The possibilities for replacement in the industrial applications operating at higher than 900° F (500° C) is somewhat smaller. In some of the moderately severe (referring to both temperature and corrosiveness) industrial environments, steels with 12 to 15 percent chromium would suffice where high-chromium stainless grades (18 percent or more) are now used. This substitution opportunity exists because engineers often specify the common grades, which have better properties (and more chromium) than needed, in order to expedite the design process. In addition, there are low-chromium (e.g., 9 percent) or chromium-free steels now under development for use in these moderately harsh environments. Even considering these new alloys, re-

Table 7-3.—High-Volume Stainless Steels

AISI stainless steel grade	Percent of domestic stainless steel production	Typical chromium compositions	Percent of chromium consumed in stainless steel	Percent of total domestic chromium consumption[a]
301	9.6%	17.0%	9.4%	4.6%
304	42.3	19.0	46.5	22.6
304N & 304L	4.0	19.0	4.4	2.1
316	3.6	17.0	3.5	1.7
316L	3.1	17.0	3.1	1.5
409	10.1	11.1	6.5	3.2
430	3.5	17.0	3.4	1.6
Other grades	23.9	NA	23.1	11.2
Total stainless	100.0%	17.3%	100.0%	48.5%

[a] Includes chromium in metal, ferroalloys, and chromite.

Columns may not add to totals because of rounding.

NA = Not applicable; chromium compositions vary greatly among these stainless steels.

SOURCE: American Iron and Steel Institute, *Quarterly Production of Stainless and Heat Resisting Raw Steel*, publication AIS-104 (1983) and U.S. Bureau of Mines, *Minerals Yearbook*, Chromium Preprint (1982).

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[2] The protection from corrosion and oxidation damage comes from the chromium oxide skin that forms at the surfaces of stainless steels. Chromium concentrations of 12 percent or higher are required for the formation of the protective skin, but since corrosion and oxidation resistance increases with chromium content, much greater concentrations are often used. AISI 304 stainless steel contains 18 to 20 percent chromium, and some superstainless grades have chromium contents of 30 percent or more.

In addition to conferring corrosion and oxidation resistance, chromium improves the hardenability and stabilizes the austenite, the highly workable, ductile, and weldable microstructure found in the majority of stainless steel grades.

placement of the high-chromium stainless steels in extremely severe industrial applications, especially those at temperatures above 1,300° or 1,400° F (700° to 800° C) appears infeasible. Much of this currently irreplaceable demand for stainless steel is in critical defense applications, the chemical processing industry, and energy facilities such as powerplants and petroleum and natural gas refineries. These applications make full use of stainless steel's impressive high-temperature corrosion and oxidation resistance and strength.

According to a 1978 report by the National Materials Advisory Board (NMAB), in a supply emergency 60 percent of the chromium used in stainless steel could be saved through the use of low- or no-chromium substitutes that are either already available or could be developed within 10 years.[3] The other 40 percent of the chromium consumed in stainless steel was found to be irreplaceable unless compensated for by design or process improvements. This amount represents approximately 20 percent of the current total domestic chromium use.

Most research on reducing the use of chromium in stainless steels is sponsored by Federal agencies. The focus is on developing alternative alloys with lower chromium contents than those stainless steels in greatest demand (e.g., AISI 304, 409, and 301) for use in moderately harsh industrial environments. In addition, R&D related to advanced surface treatment processes and ceramic and composite materials, though not motivated by chromium conservation, may uncover ways to reduce the use of stainless steel in some applications.

Low-Chromium or Chromium-Free Substitutes for Stainless Steels

Current commercial low-chromium steels are unsuitable as substitutes for stainless steel in critical applications. However, several low- or no-chromium alternatives for some grades of stainless steel are under development (table 7-4.) These new steels show promise for various moderately harsh environments but do not perform as well as high-chromium grades in extremely severe applications. Most are still at the laboratory stage of development, although some are now undergoing certification. The bulk of the research is being sponsored by Federal agencies, since private firms have little incentive at current chromium prices to develop low-chromium substitutes. (See ch. 3 for chromium price information.)

Low-chromium or chromium-free substitute alloys for the AISI 300 (austenitic) series stainless steels have received the greatest attention from researchers. Austenitic grades, most of which contain between 16 and 26 percent chromium, account for nearly 70 percent of domestic stainless steel production and for about 36 percent of all domestic chromium demand. Among this group is the very popular and versatile type 304. Excellent fabricability and mechanical properties, combined with corrosion and oxidation resistance in a wide range of environments, makes the 300 series stainless steels attractive for many applications. Unfortunately, the remarkable combination of properties that enables this great versatility is currently impossible to replicate. Consequently, a universal substitute for the entire 300 series (or even one of the particularly popular grades) is not a likely development. The promise of each of the substitutes tends to be very application- or environment-specific.

Examples of promising research on substitutes for 300 series stainless steels in moderately severe applications include:

- *DOE's Oak Ridge National Laboratory development and promotion of a modified 9 percent chromium (Cr), 1 percent molybdenum (Mo) steel (modified 9Cr-1Mo alloy).*[4] The initial objective of the laboratory was to develop a single reference material for intermediate sections of liquid metal fast breeder reactors. Currently, these reactors contain 18 percent chromium-8 percent

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[3] National Materials Advisory Board, *Contingency Plans for Chromium Utilization*, National Research Council, Commission on Sociotechnical Systems, Publication NMAB-335 (Washington D.C.: National Academy Press, 1978).

[4] Basically a standard 9Cr-1Mo alloy with additions of columbium and vanadium.

Table 7-4.—Development Status of Potential Substitutes That Could Reduce Chromium Requirements in Stainless Steel

Substitute material	Key objective	Technical status	Institutional sponsors	Economic factors and commerical status
1. Modified 9% chromium-1% molybdenum steel.	Develop single material system to replace ferritic (2.25% Cr) and austenitic (18% Cr) steels used in pressure vessels and connecting tubing in liquid metal fast breeder reactors.	Fully developed; may also find use in fossil, solar thermal, and fusion energy systems.	Oak Ridge National Laboratory.	In process of certification by ASME boiler and pressure code committee. Cheaper than 18%Cr-8%Ni stainless for indicated uses; lack of industry sponsorship may slow commercialization.
2. 12% chromium alternative to 18% chromium 304 stainless steel.	Determine feasibility of reducing Cr use in type 304 stainless.	Mechanical properties and corrosion and oxidation resistance compare favorably with type 304 stainless.	NASA-Lewis Research Center.	Laboratory stage; initial work completed in 1979.
3. Iron aluminum molybdenum (Fe-8%Al- 6%Mo) alloy strengthened by zirconium carbide (ZrC).	Develop chromium-free material for midtemperature oxidation-resistant application.	Early tests show excellent workability and oxidation resistance, ZrC strengthening mechanism could not be controlled reliably and needs additional work.	U.S. Bureau of Mines Albany Research Center.	Laboratory stage.
4. 9% chromium austenitic alloys.	Determine if other alloying elements could replace part of the chromium in stainless steels.	Tests show corrosion resistance (in less severe environments), fabricability, weldability, and mechanical properties comparable to conventional stainless grades.	INCO under U.S. Bureau of Mines sponsorship.	Laboratory stage.
5. Theoretical method to develop low-chromium austenitic stainless steel compositions.	Develop a technical tool for devising low-chromium alloys with mechanical properties equivalent to those of type 304 stainless steel.	Modeling of alternative compositions has been undertaken. No test heats have been made.	Allegheny Ludlum Steel Corp.	Could add to the stockpile of information about substitutes, but work has yet to progress to the experimental stage.
6. Manganese-aluminum steel (Fe-Mn-Al).	Develop general use alternative to chromium-nickel stainless steel.	Laboratory work shows that these alloys may be useful at cryogenic and moderate temperatures and various corrosive environments.	Studies are being conducted in many different laboratories.	Most work is still at the laboratory stage. Limited prototype testing is being done in other countries. May be cheaper than current stainless steels.
7. 6-12% chromium ferritic steels.	Develop low-chromium oxidation-resistant ferritic stainless steels.	Oxidation and creep resistance are superior to type 409 stainless.	ARMCO (producer company).	Laboratory stage.

SOURCE: Office of Technology Assessment.

nickel (Ni) (18Cr-8Ni) alloys (e.g., AISI 304, 321, 347) in the reactor vessels and heat exchangers and a 2¼Cr-1Mo alloy in the steam generators. Use of a single material in these applications eliminates, among other problems, an undesirable dissimilar metal weld at the transition joints. The modified 9Cr-1Mo alloy was found to be a promising replacement for both types of materials. The encouraging results of the research suggest that this alloy may find use in conventional power applications, as well. Although it will replace both low- and high-chromium materials, modified 9Cr-1Mo will probably yield a net chromium savings. However, chromium conservation is a byproduct of this development effort, not a primary motivation. If this new material sees widespread use in the power industry, the resultant availability and designer acceptance may encourage its use in other low or moderately hostile applications now dominated by high-chromium materials.

Nearing commercialization, this modified 9Cr-1Mo alloy is being considered by the American Society for Testing of Materials (ASTM) and by the American Society of Mechanical Engineers (ASME) boiler and pressure vessel code committee for final certification. Since use of the material entails fabrication and inspection cost savings, as well as a materials cost reduction, prospects for successful substitution are good if it is approved[5] [6] (table 7-4, item 1).

- *NASA's comparison of the mechanical properties and oxidation and corrosion resistance of reduced chromium alloys with those of type 304.* One steel, containing 12 percent chromium, 10 percent nickel, 1.5 percent silicon, 1 percent aluminum (Al), 2 percent molybdenum, and 2 percent manganese (Mn), demonstrated properties that compare favorably with 304 stainless steel and could be used for most applications (except nitric acid environments) where type 304 is currently used. This alloy conserves one-third of the chromium normally used in type 304 stainless steel[7] (table 7-4, item 2).
- *The U.S. Bureau of Mines' investigation of a chromium-free iron-aluminum-molybdenum (Fe-Al-Mo) alloy as a potential substitute for high-chromium, heat-resistant alloys.* An optimal composition for the alloy has yet to be developed, but early findings suggest that the chromium-free alloy may resist oxidation at moderate temperatures to an extent comparable to 300 series stainless[8] [9] (table 7-4, item 3).
- *The Bureau of Mines' work on reduced-chromium substitutes for high-performance stainless steels (e.g., type 310 with 25 percent chromium) used in elevated-temperature, severely corrosive environments.* Steels containing chromium (12 to 17 percent), nickel, and aluminum are being studied in this program. The Albany Research Center of the Bureau of Mines has been successful in reducing the chromium content to 12 percent. One 12 percent chromium substitute has about three times the sulfidation-resistance of, and approximately equivalent mechanical properties to type 310 stainless steel.[10]
- *The Bureau of Mines' study of low-chromium stainless steels for high-temperature, oxidation-resistant applications.* Research has shown that steels having 8 to 12 percent chromium with additions of aluminum and silicon can have excellent oxidation-resistance and mechanical properties (to 800° C). These alloys are potential substitutes for 18Cr-8Ni stainless steels in

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[5] Robert R. Irving, "What's This Steel They're Raving About Down in Tennessee?" *Iron Age*, June 25, 1982.

[6] V. K. Sikka and P. Patriarca, *Data Package for Modified 9Cr-1Mo Alloy* (Oak Ridge, TN: Oak Ridge National Laboratory, December 1983).

[7] Joseph R. Stephens, Charles A. Barrett, and Charles A. Gyorgak, "Mechanical Properties and Oxidation and Corrosion Resistance of Reduced-Chromium 304 Stainless Steel Alloys," NASA Technical Paper 1557, November 1979.

[8] J. S. Dunning, *An Iron-Aluminum-Molybdenum Alloy as a Chromium-Free Stainless Steel Substitute*, U.S. Department of the Interior, Bureau of Mines Report of Investigations 8654 (Washington, DC: U.S. Government Printing Office, 1982).

[9] J. S. Dunning, M. L. Glenn, and H. W. Leavenworth, "Substitutes for Chromium in Stainless Steels," *Metal Progress*, October 1984, p. 23.

[10] Ibid., p. 23.

some applications. Further long-range research to qualify other important properties such as high-temperature stability, weldability, and age-hardening characteristics is underway.[11]

- *Research sponsored by the Bureau of Mines at the Inco Alloy Products Research Center aimed at replacing some of the chromium now needed for stainless steels used in corrosive environments.* The findings suggest that it may be feasible, with additions of nickel, molybdenum, copper, and vanadium, to produce 9 percent chromium austenitic stainless steels with corrosion resistance, hot working behavior, weldability, and mechanical properties comparable to those of conventional grades. These low-chromium alloys, while not adequate for more severe environments, could be used in decorative, aqueous, and some industrial applications[12] (table 7-4 item 3).
- *Allegheny Ludlum Steel Corp. Research Center's development of a theoretical model for devising new reduced chromium alloys that would duplicate the excellent mechanical properties of type 304 stainless steel, although not its corrosion resistance.* Actual alloys have not been developed from these theoretical compositions, which range from 6 to 16 percent chromium, but some of them could be suitable as substitutes in noncritical applications[13] (table 7-4 item 5).
- *Various researchers' work with iron-manganese-aluminum (Fe-Mn-Al) steels.* The Fe-Mn-Al steels contain no chromium, but may consist of up to one-third manganese, another strategic material. The high aluminum content of the Fe-Mn-Al steels provides oxidation resistance. Though most of the work is still preliminary, these alloys show promise as replacements for 300 series (chromium-nickel) stainless steels in some moderately corrosive environments.

Photo credit: U.S. Department of the Interior, Bureau of Mines

An 80-pound heat of an experimental low-chromium stainless steel is poured into a split steel mold at the Bureau of Mines, Albany Research Center

With heat treatment, the Fe-Mn-Al steels demonstrate excellent mechanical properties, in some cases as good as or better than type 304. In addition, they are 10 percent lighter (and have greater strength-to-weight ratios) than nickel-chromium stainless steels. Though the economics depend on the relative costs of manganese, aluminum, chromium, and nickel and the size of the production runs, Fe-Mn-Al alloys are likely to be less costly than 300 series grades[14] [15] (table 7-4, item 6).

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[11] Ibid., p. 23.

[12] S. Floreen, "An Examination of Chromium Substitution in Stainless Steels," *Metallurgical Transactions A*, November 1982.

[13] R. A. Lula, "Potential Areas for Chromium Conservation in Stainless Steels," in *Technical Aspects of Critical Materials Use by the Steel Industry*, vol. IIA, NBSIR 83-2679-2 (Washington, DC: U.S. Government Printing Office, June 1983).

[14] Samir K. Banerji, "The 1982 Status Report on Fe-Mn-Al Steels," as cited in *Technical Aspects of Critical Materials Use by the Steel Industry*," vol. IIB, NBSIR 83-2679-2, June 1983.

[15] Rosie Wang, "New Stainless Alloy is Less Costly," *American Metal Market*, Sept. 19, 1983.

Information requirements for stainless steel substitutes are under evaluation by the Metal Properties Council, Inc. (MPC), an organization set up by industry and technical societies in 1966 to provide engineering data on materials. MPC established a Task Group on Critical Materials Substitution in 1981. An initial MPC task group report,[16] issued in 1983, noted a gap on the technical information about alternative low-chromium compositions for stainless steel. Most of the available data was from laboratory investigations, with little information developed about processing and fabrication of these compositions, or about how they held up in service environments—essential information if industry were to use these substitutes during a protracted supply shortage. Subsequently, MPC has decided to focus on chromium substitution options for 18 percent chromium-8 percent nickel stainless steels used in room-temperature to moderately high-temperature (up to 1,200° F) applications.[17] These applications comprise the highest volume uses for stainless steels, including many for which a decrease in corrosion resistance may be acceptable to some consumers in times of a supply shortage. MPC is now evaluating future steps, such as developing alternative compositions that duplicate all metallurgical and mechanical properties of the popular grades of steel, except corrosion resistance. MPC is preparing a survey to gain input from industry.

The AISI 400 series, accounting for about 20 percent of domestic stainless steel production, is the second largest class of stainless steels. Type 409, which contains approximately 11 percent chromium, is the second most popular stainless steel. It accounts for about half the production of 400 series grades and is used principally in the catalytic converter housings in automotive exhaust systems.

ARMCO is exploring several lower chromium alternatives to ferritic (400 series) stainless steels containing 12 percent chromium. These new alloys, still at the laboratory stage, may be promising substitutes for stainless steel used in the catalytic converter shell of automobiles. ARMCO reports that its 6.6 percent chromium alloy 6SR (scale resistant) is more oxidation- and creep-resistant than 409 stainless steel. Unlike, the other substitutes described above, the SR alloys (which also include 12SR, a potential 12 percent chromium substitute for some 18 percent chromium grades) are being researched in the producer industry. As a result, the institutional barriers to the acceptance of these SR alloys are relatively low[18] (table 7-4, item 7).

These substitutes are all in various stages of development. Other than the modified 9Cr-1Mo alloy, which is undergoing certification, the replacement alloys have not yet advanced beyond the laboratory level of investigation in the United States. The development of the chromium-free substitutes, such as the ferritic Fe-Al-Mo and the austenitic Fe-Mn-Al alloys, designed for elevated-temperature oxidation/corrosion-resistant service, probably involve the longest range, highest risk research. The low-chromium alloys also require additional study, but technical success is in general less speculative. Extensive additional testing of mechanical properties, phase stability, and other physical properties of any of the newly designed alloys, as well as ease of processing, could take several years. Even if these alloys overcome the initial hurdles, economic feasibility will remain in question. Without large markets in place, these alloys cannot be produced cheaply enough (due to poor economies of scale) to compete effectively with the current high-volume stainless steel products.

Advanced Surface Treatment Technologies and Processes

Most of the chromium in stainless steel is present solely for corrosion and oxidation resistance. Chromium's secondary roles can be met with the use of other alloying elements or processing techniques. Since corrosion and oxidation resistance is only needed at the surface, the chromium on the interior of the stainless steel is nonessential. Surface modification techniques can endow low- or no-chromium materials with corrosion and oxidation resistance sufficient to substitute for stainless steels in some applications. Advanced surface treatment techniques may also improve wear resistance, thus extending product life.

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[16] The Metal Properties Council, Inc., "Task Group on Critical Materials" (New York: The Metal Properties Council, Inc., 1983).

[17] Private communication with R. A. Lula and officials of the MPC.

[18] Joseph A. Douthett, "Substitute Stainless Steels With Less Chromium," in *Conservation and Substitution Technology for Critical Materials*, vol. I, NBSIR 82-2495 (Springfield, VA: National Technical Information Service, April 1982).

Existing fully developed surface treatment technologies—e.g., plating steels with chromium, nickel, cadmium, or zinc or welding a stainless steel overlay to nonchromium alloys—have been used for decades in a large number of applications, but there are constraints in their use. Fabricated parts and brittle metals cannot be clad, for example, and clad materials are difficult to weld. Claddings sometimes separate from the base metal, with potentially disastrous results.

A number of advanced processes now under development or in the early stages of commercialization may broaden applications for surface treatment. One advanced coating technique that can compete directly with stainless steels in some applications is the DILEX process. This technique involves the diffusion of chromium (or other elements) into the surface of a ferrous part that is placed in a lead bath. The surface alloy typically contains 25 percent or more chromium (and possesses excellent corrosion and oxidation resistance), while the underlying substrate contains little chromium. The cost of continuously processed DILEX strips is currently competitive with stainless steel products. In addition, parts and components that are difficult to fabricate from stainless steel can sometimes be produced more easily with the DILEX process.[19]

Surface alloying with lasers (by processes commonly referred to by their United Technologies trade names, LASERGLAZING and LAYERGLAZING) can provide corrosion and oxidation protection and wear resistance to materials. LASERGLAZING can improve erosion and corrosion properties through elimination of surface porosity, and can produce a wear-resistant surface that could extend the life of steels used in metal cutting and grinding. LAYERGLAZING can be used to build entire parts (e.g., turbine discs) through continuous melting of very thin layers of alloy at the surface. Such processes permit tight control over the composition of the alloy and can also reduce part rejections, since flaws detected in processing can be reglazed immediately. While laser techniques have impressive capabilities, these processes are not presently as cost effective as some of the more established surface modification practices, such as roll bonding.

A recent technological advance, ion implantation, holds long-term promise as a way of improving the wear- and corrosion-resistance of parts, thus helping conserve strategic materials through extending product life or reducing the need for chromium in corrosion-resistant applications. In ion implantation, high-energy ions of alloying elements are embedded into the surface of the workpiece to produce a surface layer of 100 to 1,000 angstroms that is an integral part of the substrate. Advantages of this technique include excellent coating-substrate adhesion (owing to the lack of a sharp boundary between the two), no dimensional alteration of the substrate, and low processing temperatures. Elements such as carbon, nitrogen, chromium, and nickel can be implanted, but the resulting properties are not as dependent on the type of ion as on the mechanical deformation it causes to the matrix surface. Therefore, the choice of an ion is based on its mechanical effect in the host material, not on its own inherent corrosion- or oxidation-resistant properties.[20]

Ion implantation has been shown to extend the life of cobalt-based cemented carbides and tool steels when carbon and/or nitrogen are applied. Implantation of yttrium in diesel fuel injection pumps reportedly dramatically improves wear resistance in comparison with chrome plating. Bureau of Mines-supported research has shown that ion implantation can protect plain carbon steels against mild aqueous corrosion.

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[19] Ray J. Van Thyne, "Conservation of Critical Metals Utilizing Surface Alloying," as cited in *Conservation and Substitution Technology for Critical Materials*, vol. II, NBSIR 82-2495, April 1982.

[20] Charles River Associates, *New Metals Processing Technologies*, OTA contract report, December 1983, p. 46.

Ion implantation techniques, first developed in Great Britain, are fully commercialized in the semiconductor industry. For metallurgical applications, ion implantation is at the operational prototype stage—commercial machines are being developed, but there has been little market penetration.[21] Substantial technical and economic constraints impede its use for large-volume metallurgical uses. To be effective in providing corrosion resistance, ionic density must be much greater than in semiconductor applications. Commercial equipment capable of handling this higher beam density has yet to be developed and appears to be prohibitively expensive at this time. High capital costs and limited product size and production rates are key constraints acting against this technique's widespread use.

All surface treatment techniques have drawbacks. If the surface layer fails, the exposed substrate would be vulnerable to corrosion. Fabrication and construction with surface-treated materials is more difficult and costly than with monolithic materials. Special welding and joining techniques must be used to assure that the base material does not become exposed. Edges of the material must be treated to maintain protection. These welding and joining techniques are subject to separate research and development efforts. In addition, surface treatment can be very expensive, so there are major efforts aimed at improving the process economics of these techniques.

Surface treatments also face nontechnical and noneconomic hurdles. Designers and consumers often resist use of surface modification processes in new applications where solid monolithic alloys perform satisfactorily.

Chromium Substitution in Alloy Steels

About 15 percent of U.S. metallurgical chromium (10 percent of total domestic chromium) is consumed in alloy steels. Chromium is used in these steels primarily as a hardening agent. Although other elements, such as molybdenum, silicon, and nickel, can be used for this purpose, chromium and manganese are currently the most cost-effective hardenability enhancers. Because chromium's hardenability characteristics are more easily replicated than its corrosion and oxidation attributes, fewer technical problems exist in developing adequate substitutes for alloy steels than for stainless steels. In its 1978 Chromium Utilization study, the NMAB concluded that 80 percent of the chromium used in alloy steels could be replaced either now or after a short-term R&D effort.

The chromium contents of alloy steels typically range from less than 1 to 4 percent, although some grades have as much as 9 percent. Compared to carbon steels, these steels have improved strength, wear resistance, and hardenability. They are chosen when parts (e.g., bearings, gears, shafts) will be highly stressed over a long service life.

Several alternative chromium-free alloy compositions are under investigation as substitutes for large-volume alloy steels. These alloys have been designed to duplicate the most important properties of the steels they would replace, so that processing changes and design changes could be minimized if they were to be used as replacement steels.

Work at the International Harvester Co., sponsored by the Bureau of Mines, was aimed at the design of chromium-free substitutes for two alloy steels that together account for about 60 percent of the chromium used in constructional alloys, or about 6 percent of total U.S. chromium demand. These Cr-Mo grades (AISI 4100 series) and the Ni-Cr-Mo grades (8600 series) have been used for decades, and as a result, current designs for parts and manufacturing processes are adapted to these steels. The chromium in these grades was substituted with manganese, molybdenum, and nickel. Silicon, another common hardening agent, was not used because alloy steel producers have little experience with the high silicon levels (0.6 percent Si) required to achieve the desired hardenability. The compositions of the Mn-Ni-Mo and Mn-Mo replacement steels are shown in table 7-5.

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[21] Carnegie-Mellon University, Department of Engineering and Public Policy, Department of Social Sciences, and School of Urban and Public Affairs, *The Potential of Surface Treatment Technologies in Reducing U.S. Vulnerability to Strategic Materials*, Pittsburgh, PA, April 1984.

To minimize the disruption entailed in shifting to new steels, the new chromium-free steels were designed to be produced using prevalent U.S. production practices. Moreover, the experimental substitutes have the same microstructure, heat treatment response, and mechanical properties as the steels they would replace, and therefore would provide equivalent engineering performance. So far, actual production of these steels has been limited to 100-pound experimental test heats, thus the steels' characteristics in large-scale commercial production have not been demonstrated.

The second phase of this program—to produce larger heats for testing—was delayed, owing to the financial status of the contractor. However, in 1984 the Bureau released a request for proposal which calls for about a 3,000-pound test heat. When completed, this phase of the program will provide better information for the possible transfer of this technology to industry.

In the original economic analysis (based on 1981 raw materials costs), these steels were not found to be cost effective. However, the Mn-Mo replacement for the 8600 series steels may become economical with the moderate chromium price increases that would be expected under steady economic and political conditions. The other replacements (Mn-Ni-Mo for 8600 and both Mn-Ni-Mo and Mn-Mo for 4100) would become economical only with the drastic price increases (on the order of tenfold for chromium ore and fourfold for ferrochromium) that would accompany severe chromium supply disruptions, such as a complete cutoff from South African supplies. To facilitate their use in such an emergency, the researchers recommended additional testing of these steels to determine equivalency of these steels under typical production practices by U.S. producers.[22]

Development of these alternative steels was facilitated through International Harvester's CHAT (Computer Harmonizing Applications Tailored) system, which first identifies metallurgical properties needed for particular parts and then selects the least-cost alternatives from AISI and SAE steels that are available. Use of computerized information systems of this sort could facilitate the development of a strategic materials substitution information system that could be used in an emergency.

Reducing Cobalt and Chromium Used in Superalloys for High-Temperature Applications

Superalloys, used in jet engines, industrial gas turbines, and a widening spectrum of other industrial applications, account for 30 to 40

Table 7-5.—Ladle Analysis Ranges for the Chrome-Free Replacement Composiitons for Standard 4118 and 8620 Steels (In percent)

	4100 type steel			8600 type steel		
Chemistry ladle range	AISI-4118 steel	Mn-Ni-Mo replacement	Mn-Mo replacement	AISI-8620 steel	Mn-Ni-Mo replacement	Mn-Mo replacement
Carbon	0.18-0.23	0.16-0.21	0.16-0.21	0.18-0.23	0.16-0.21	0.16-0.21
Manganese	0.70	0.90	1.00-1.30	0.70-0.90	1.00-1.30	1.00-1.30
Chromium	0.40-0.60	r	r	0.40-0.60	r	r
Nickel	r	0.20-0.40	r	0.40-0.70	0.40-0.70	r
Molybdenum	0.08-0.15	0.15-0.25	0.25-0.35	0.15-0.25	0.25-0.35	0.35-0.45

r—residual.
silicon range = 0.15-0.35%; sulfur = 0.05% maximum; phosphorus = 0.04% maximum.

SOURCE: Carl J. Keith and V. K. Sharma, *Development of Chromium-Free Grades of Constructional Alloy Steels*, U.S. Bureau of Mines contract No. J0113104, May 1983.

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[22] Carl J. Keith and V. K. Sharma, *Development of Chromium-Free Grades of Constructional Alloy Steels*, U.S. Department of the Interior, Bureau of Mines' contract No. J0113104, May 1983.

percent of U.S. cobalt consumption. Only a small portion of U.S. chromium consumption goes into superalloys—about 3 percent in 1982. This amount is in the form of highly purified ferrochromium and chromium metal. Other materials used in superalloys include nickel, aluminum, titanium, and a number of minor alloying elements, including columbium (niobium) and tantalum—two second-tier strategic materials for which the United States is import-dependent.

While many superalloys do not contain cobalt, the use of cobalt has increased over time because it improves the weldability of some superalloys, contributes to their strength, and also enhances oxidation and corrosion resistance. Chromium is currently essential in all superalloys.

Importance of Superalloys to the Aerospace Industry

Improved jet engine performance has been highly dependent on development of new superalloys[23] that extend the maximum operating temperature of the engine yet are still able to withstand the high mechanical and thermal stress, oxidation, and hot corrosion that occurs in the hot section parts of a jet engine. Through complex adjustments in composition and processing, the temperature capability of superalloys has been extended from about 1,400° F in 1940 to about 1,950° F today (some superalloys now in use have operating temperatures of about 2,100° F), as shown in figure 7-1. In addition, the required life of various components (the minimum predictable time before overhaul or replacement) has also increased significantly.

Each individual component in the hot section of a jet engine, such as turbine blades, vanes, and discs, requires a superalloy with a different range of properties—so that development of an adequate substitute for one part does not mean that it can also substitute for other parts. In addition, each of the U.S. jet engine manufacturers maintain separate specifications for superalloys that can be used in each part. Today, there are well over 100 superalloys used domestically, but some of these may be certified for use only by one engine manufacturer. Table 7-6 shows representative superalloys used in the different parts of the hot sections of current jet engines.

As superalloys have become more specialized, their costs have escalated, so that it often takes a decade or more and several million dollars to bring a promising new alloy even to the engine testing stage. Initial development of a new superalloy in the laboratory for disc or blade applications constitutes only part of the total effort. Prior to engine qualification and use, a complete design data base, specifications and standards, component and machine testing, and commercial-scale heats must be demonstrated. Without a pressing need for substitutes, industry alone is unlikely to make this kind of commitment.

Substitution Prospects

From the standpoint of reducing U.S. vulnerability, backing out or reducing cobalt and chromium use in superalloys would be highly desirable—but only if they could be achieved without impairing the push toward higher performance in military applications. Continued increase in performance is the primary objective behind most government and industrial research aimed at developing new hot-section materials, although many of these materials could have the side benefit of reducing strategic materials requirements. Figure 7-2 shows NASA estimates of the approximate date for introduction of some of these higher temperature materials in aircraft. These materials are discussed later in this chapter.

Superalloys will almost certainly remain the primary structural material in turbine blades

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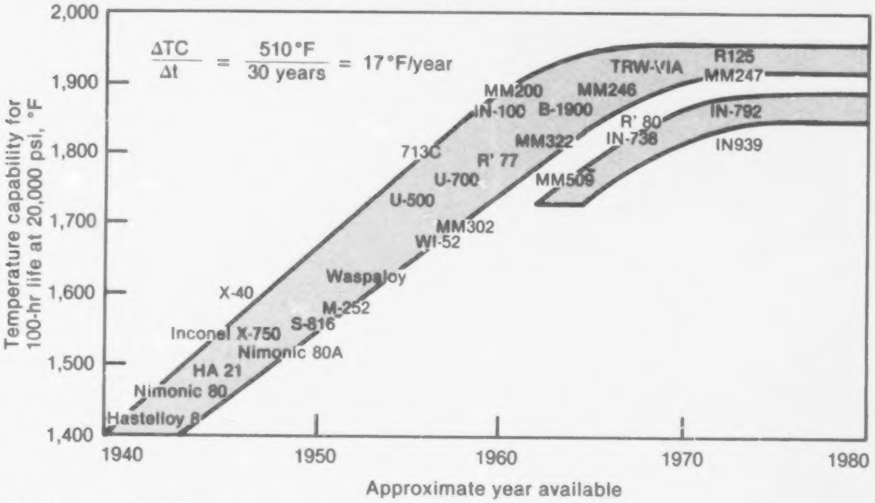
[23] The analysis of superalloy substitution potential in this section is drawn in large part from Richard C. H. Parkinson, *Substitution for Cobalt and Chromium in the Aircraft Gas Turbine Engine*, OTA staff background paper, September 1983. It should be noted that superalloy use is spreading to many nonaerospace applications, such as oil country tubulars, heavy duty tooling, pulp and paper production, medical and dental uses, and glass manufacture. In these applications, superalloys were substituted for other materials that could again be used in an emergency, although possibly with some performance costs. In the case of gas turbine engines used in jet aircraft, however, alternatives to superalloys are not currently available, and moreover are not likely to be developed in this century. Thus, aerospace uses remain the most demanding and critical superalloy applications.

Figure 7-1.—Temperature Capability of Superalloys



SOURCE: Garrett Turbine Engine Co.

for at least the next 20 to 30 years. During this period, complete elimination of cobalt and chromium in jet engines is highly unlikely, although use of alternate alloys, wider use of coatings, and adoption of more efficient processing technologies could reduce use of these materials in individual applications.

In the long term, probably not before the second decade of the next century, a variety of nonmetallic materials (e.g., advanced ceramics and carbon-carbon composites) may be developed sufficiently to be widely used in some hot-section parts of human-rated jet engines. If so, chromium, cobalt, and other metals then may begin to be phased out of jet engines. Actual production dates for the first engines containing significant amounts of nonmetallic materials is likely to be well beyond the year 2000.

In the sections that follow, near-term (to 1990), medium-term (1990 to 2000), and long-term prospects for reduced chromium and cobalt usage in jet engines are selectively discussed, under the assumption that R&D efforts continue at approximately their present levels. Institutional factors that could affect the extent to which various substitution potentials are adopted are discussed in the concluding section of this chapter.

Near-Term Prospects for Cobalt Substitution (to 1990)

Cobalt supply insecurities in the late 1970s led U.S. jet engine makers to substitute already developed nickel-base superalloys for cobalt-base alloys wherever possible. A conspicuous example of this was the substitution of the already developed and qualified cobalt-free superalloy Inconel 718 for Waspaloy (13 percent cobalt) in turbine disk applications below 700° C. Inconel 718, which contains a large amount of niobium, a strategic material imported largely from Brazil, continues to be used in these applications owing to its comparative cheapness and ease of fabrication. Other superalloy substitutions included replacement of cobalt-base vanes with cobalt-free nickel-base superalloys.

Cobalt prices are unlikely to stimulate further substitution in the near term. Easy to accomplish substitutions have already taken place. As a practical matter, adoption of lower chromium or cobalt substitutes by engine makers is not likely unless substantial improvements in properties, higher temperature capabilities, or ease in fabrication accrue, as well.

Processing Advances.—As a result, the greatest opportunities for cobalt and chromium conser-

Table 7-6.—Typical Structural Alloys Used for Hot-Section Components

		Composition (percent weight)					Nominal operating conditions	
Component	Alloy	Ni	Co	Cr	Fe	Form	Stress	Surface temperature (°F)
						—Large grains--		
Combuster liner	Hastelloy X	**48**	1.5	22	**18.5**	Sheet	Low	1600
	HA-188	22	**41**	22	—	Sheet	Low	1600
						—Large grains—		
Turbine valve	MA-754	**78**	—	20	1	ODS + HIP, ODS + forge		1900 +
	MAR-M200	**60**	10	9	—	DS		1900
	MAR-M247	**60**	10	8	—	CC, DS	Moderate to low	1800-1850
	MAR-M509	10	**55**	23.5	—	CC		1800 +
	X-40	10.5	**56**	25.5	—	CC		1800 +
	IN-713	**72.5**	—	13.5	—	CC		1600
	Rene-77	**55**	15	15	—	CC		1600
						—Large grains—		
Turbine blade	Alloy 454	**62.5**	5	10	—	SC		1900
	MAR-M200	**60**	10	9	—	DS		1850
	MAR-M247	**60**	10	8	—	CC, DS		1800-1850
	B-1900	**65**	10	8	—	DS	High	1800
	Rene-80	**60.5**	9.5	14	—	CC		1750
	IN-713LC	**72.3**	—	12	—	CC		1600
	Rene-77	**55**	15	15	—	CC	1600	
						—Small grains—		—Rim temperature—
Turbine disc	IN-100	**56**	18.5	12.5	—	PM + HIP, PM + forged		1300
	MERL-76	**54.1**	18.5	12.4	—	PM + HIP, PM + forged		1300
	Astroloy	**55.5**	17	15	—	PM + HIP, PM + forged, forged		1300
	Waspaloy	**58**	13.5	19.5	—	Forged		1250
	Rene-95	**61.3**	9	14	—	PM + forged	High	1200
	IN-718	**53**	—	19	**18**	Forged		1200
	IN-901	**45**	—	12.5	**34**	Forged		1100
	A-286	**25.5**	—	15	**55**	Forged		1000
						—Small grains—		
Case	Waspaloy	**58**	13.5	19.5	—	Sheet, forged		1300
	IN-718	**53**	—	19	**18**	Sheet, CC, forged	High	1200
	IN-901	**45**	—	12.5	**34**	Forged		1100
	A-286	**25.5**	—	15	**55**	Forged		1000

NOTES: CC—Conventionally cast.
DS—Cast and directionally solidified polycrystal.
SC—Case and directionally solidified single crystal.
PM—Powder metallurgy.
ODS—Oxide dispersion strengthened.
HIP—Hot-isostatic pressing.
Alloy base compositions are shown in boldface type.

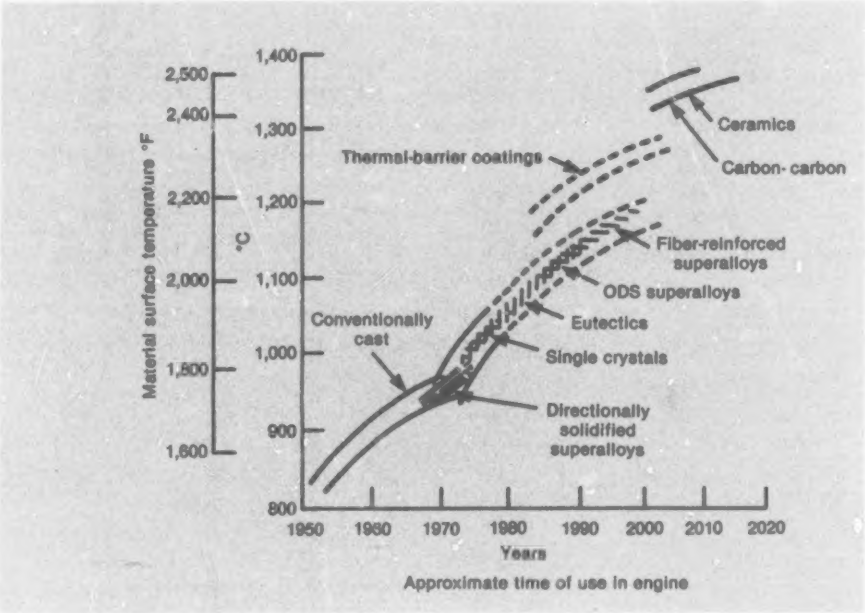
SOURCE: Office of Technology Assessment.

vation in superalloys in the near term lie in continued commercialization of advanced processing technologies, which have the incidental effect of improving cobalt or chromium yields in parts or of extending the life of components.

Several of these new metals processing technologies are currently being adopted by industry, as is discussed in chapter 6. Powder metallurgy, with its potential to produce parts that are close to their final shape, can dramatically reduce reject rates and scrap generation in fabrication of engine components. Two powder metallurgy processes used in conjunction with each other—hot isostatic pressing (HIP) and isothermal forging—are now used commercially, although equipment costs are high.

Improved material utilization would be achieved if HIP parts did not have to be hot worked. This is now essential in order to over-

Figure 7-2.—Temperature Capabilities of Turbine Blade Materials



SOURCE: National Aeronautics and Space Administration.

come fatigue problems, but reduces product yields. The U.S. Air Force Office of Scientific Research is supporting research in this area to improve the final quality of superalloy components.

Hot isostatic pressing can also be used to rejuvenate turbine vanes and blades, potentially doubling the operating life of parts. So far, HIP rejuvenation has been used primarily in industrial gas turbines but is not yet widely used for worn aircraft parts. As discussed in chapter 6, life cycle extension techniques are under intensive investigation by the Air Force, and some jet engine parts are now being saved (rather than sold as scrap), pending possible improvements in rejuvenation technologies. Most obsolete jet engine parts, however, continue to be sold as scrap, and most of the scrap is downgraded to less demanding uses.

By the end of the 1980s, additional jet engine applications for cobalt-free oxide dispersion strengthened (ODS) superalloys are probable. These nickel- and iron-based superalloys are produced through a mechanical alloying process, first developed in 1968. Although still considered an emerging technology, rapid growth in ODS production is expected as new applications are accepted.

All currently available ODS superalloys are cobalt free and are marketed by the Inco Alloy Products Co. One ODS alloy, MA-754, has been used for years in high-pressure turbine vanes of military aircraft produced by General Electric. New applications for ODS alloys in combustor linings and turbine blades are being investigated as part of NASA's Materials for Advanced Turbine Engine (MATE) Program.

NASA and Pratt & Whitney Aircraft are currently evaluating another cobalt-free ODS alloy (MA-956) for use in combustor linings. Early results suggest that MA 956, coupled with design changes, could extend the operational life of these linings by up to four times compared to existing linings. It can also be used at a higher temperature than a commonly used liner material, Hastelloy X (which contains 1.5 percent cobalt).

Although ODS alloys are superior at high temperatures (i.e., 2,100° F), their poorer performance in intermediate temperature ranges (i.e., 1,400° to 1,600° F) has so far prevented their use in turbine blades. However, NASA, in conjunction with the Garrett Turbine Engine Co., is evaluating the recently developed cobalt-free ODS alloy MA-6000, for turbine blade applications. Research suggests that an increase in surface metal temperature of 150° F over the best current superalloy blade material may be feasible.

ODS alloys are more expensive than conventional superalloys. With expanded markets, however, finished part costs have declined. Additional price reductions could arise if the market expands into turbine blade and industrial applications. Current production of these alloys is about 120,000 pounds per year, but is growing rapidly.

Coatings.—Continuing near-term progress in enhancing the surface properties of hot-section components through use of coatings is also expected. Coatings of one sort or another have been used since the 1960s and have extended the life of parts significantly. Thermal barrier coatings (TBCs), now used on combustor linings and vane platforms, provide oxidation and hot corrosion resistance through a metallic bond coat (often containing chromium), which, in turn, is covered with a thin ceramic coat to provide thermal insulation. TBCs have yet to be applied to turbine airfoil surfaces because peeling problems have not been completely overcome. However, they may may be used on airfoil surfaces by the end of the decade.

Coatings (or other surface treatments) may some day permit reduced use of chromium in superalloys—although near-term prospects are very limited. Chromium's primary function in superalloys is to provide oxidation and hot-corrosion resistance at the surface of components. Most superalloys contain several times as much chromium as strictly needed to provide this surface protection. As an insurance measure, chromium is added throughout the alloy, even though it is only needed at the surface.

Aside from its absolutely essential role in corrosion resistance, the high levels of chromium throughout monolithic superalloys may not be needed. In theory, conservation of chromium and improved mechanical properties could be achieved if a safe way could be found to put chromium only at the surface of components, leaving the rest of the part chromium free. Presently, coating or cladding of a chromium-free base alloy is not acceptable, owing to the possibility of a disastrous crack forming in the coating. Other advanced surface treatment processes have yet to be applied for the specific purpose of reducing chromium content.

From the above discussion it would appear that prospects for cobalt substitution in superalloys are quite limited in the near term, and that few available alternatives are ready for use by engine manufacturers. Chromium substitution prospects are even more limited.

Medium-Term Prospects for Further Cobalt and Chromium Substitution (1990-2000)

Over the next 10 to 15 years, only substitute materials that are now approaching qualification and approval for jet engine use are likely to be useful in reducing U.S. dependency on imported strategic materials. The long lead time entailed in testing and certification of new materials and the time it takes for designers to become familiar with them make it unlikely that new materials or processes not now being actively developed will be in commercial use before the last half of the 1990s.

Several cobalt-free or low-cobalt alternative materials have been investigated under NASA sponsorship (Conservation of Strategic Aerospace Materials Program, established in 1981, and pre-COSAM research activities.) These substitutes could provide alternative compositions for six widely used superalloys. Table 7-7 shows currently used superalloys selected for substitution research. Preliminary laboratory experiments suggest that cobalt may not be needed in the high-volume Udimet 700 type superalloy (18 percent cobalt) which is used in turbine discs and blades. One evaluation of the initial COSAM research hypothesized that

Table 7-7.—Nickel-Base Superalloys Selected for Cobalt Substitution Research by NASA

Alloy	Typical engine application	Form	Remarks	Cobalt content (% weight)
WASPALOY ...	Turbine disc	Forged	Highest use wrought alloy in current engines	13.5
UDIMET-700 ...	Turbine disc	Forged	Similar alloys used in various forms and applications	18.5
(LC) ASTROLOY	Turbine disc	as-hip-powder		
(RENE 77)	Turbine blades	Cast		
MAR-M247	Turbine blades and wheels	Cast	Conventially cast, DS and single crystal	10.0
RENE 150	Turbine blades	DS-Cast	Highly complex directionally cast alloy	12.0

SOURCE: Adapted from Joseph R. Stephens, *A Status Review of NASA's COSAM (Conservation of Strategic Aerospace Materials) Program*, NASA Technical Memorandum 82852 (Springfield, VA: National Technical Information Service, May 1982).

while definite conclusions are premature, it may be possible to cut by one-half or even eliminate cobalt now used in some nickel-based superalloys with little or no effects on mechanical properties or environmental resistance. (An estimated 2.15 million pounds of cobalt was contained in nickel-based superalloy primary products in 1980, according to the NMAB. This comprised about one-eighth of total apparent cobalt consumption in that year.)[24]

The COSAM substitutes are still in the laboratory stage of development and are many years away from actual use in a jet engine. In theory, the COSAM alternatives could be brought on line more quickly than an entirely new material, since only slight adjustments in manufacturing processes may be needed to produce the low-cobalt substitutes. However, to commercialize these alloys fully could still require 6 to 7 years and $6 million to $9 million per application—a commitment that engine makers will find difficult to justify, given current low-cobalt prices. Hence, their post-COSAM development may be delayed until a perceived need arises.

Over the next 10 to 15 years, strategic materials conservation could also be a side benefit from several advanced superalloy production techniques that are approaching commercialization—simply because some of the experimental prototypes and research materials happen to contain little or no cobalt. These processes may not necessarily conserve strategic materials over the long run, however, if it turns out that cobalt provides a performance benefit over the experimental prototypes.

One group of these new processing methods is "rapid solidification," in which metals are solidified so quickly that the resulting distribution of elements is nearly homogeneous, having few inclusions that could initiate fatigue cracks. Moreover, previously unattainable alloy compositions with superior properties can be obtained in some cases. Experimental cobalt-free superalloy powders produced through various rapid solidification processes have been shown in early experiments to have some advantages over conventionally processed alloys. Detailed information on rapid solidification processes and their prospects as substitutes for strategic materials is provided in the Advanced Materials section of this chapter.

The capability to produce directionally solidified eutectic superalloys is another of the recent processing advances. Over the past two decades considerable effort has been devoted to developing this technique. When superalloys are produced in this manner, they are strengthened by the formation of microscopic carbide or intermetallic fiber reinforcements. Most of the experimental alloys have comparatively low levels of chromium and cobalt—4 percent and 3 to 10 percent respectively. As with other advanced processes and materials, the key objective of eutectics development is not to conserve strategic materials, but to increase temperature capabilities of turbine blades and vanes. Eutectic superalloys could increase the allowable operating temperature of these components by about 100° F compared to currently available single-crystal alloys.

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[24] National Materials Advisory Board, *Cobalt Conservation Through Technological Alternatives*, National Research Council. Publication NMAB-406 (Washington, DC: National Academy Press, 1983), pp. 24 and 47.

Although work on eutectic alloys is progressing, they have yet to receive qualification for engine use. Technical problems include inferior transverse properties and poor oxidation and corrosion resistance. Cost of these alloys is high because the processing times are high; a eutectic blade can be withdrawn from the furnace at only about one-fourth inch per hour. However, eutectic R&D has had active support by engine producers (General Electric and United Technologies) as well as scientific support at government laboratories and universities.

The medium-term (1990-2000) prospects for reducing cobalt and chromium in jet engines are difficult to assess because new materials will be used as new jet engines are introduced into military and civilian aircraft. The selection of these materials will be performance driven, and while some materials may contain little or no cobalt, others almost certainly will. Development of the COSAM alternatives to the point of commercial use is possible over this period, but these materials will serve as substitutes for currently used superalloys which will comprise a declining portion of superalloy use. It is also possible that, over this period, a breakthrough in basic science will occur which will lead to a better understanding of the precise role of cobalt in superalloys, with possible reductions of cobalt in the design of new alloys. Improved understanding of the role of cobalt and other strategic materials in superalloys is a key purpose of the COSAM program.

Long-Term Prospects

Over the long term, several classes of new materials that are completely free of cobalt or chromium may come into use. These alternatives are being actively pursued because of their potential to extend the maximum operating temperatures (and thus performance) of turbine blades beyond the current limits of around 1,150° C or 2,100° F. These materials include ceramics, composites, and monolithic intermetallic compounds (or long-range order materials) and are discussed in detail in the next section. Table 7-8 summarizes potential applications for these advanced materials in the hot section of jet engines.

Table 7-8.—Use of Structural Materials Under Development to Reduce Cobalt and Chromium Usage in Hot-Section Parts

	Composition (percent weight)		
Material	Co	Cr	Suitable components
Rapid solidification processed superalloys	Varies	Varies	Combustor liners; cases; turbine blades, vanes, discs, seals.
Long-range order (intermetallics):			
Ni	—	—	HP turbine discs (combustor liners; HP turbine vanes, blades)
Ti	—	—	LP turbine discs, blades, vanes; cases.
Fe	—	—	Combustor liners; LP turbine discs, blades, vanes; cases
Directionally solidified eutectics	3-10	4	Turbine blades, vanes
Oxide dispersion strengthened superalloys	—	15-20	Turbine vanes; (combustor liners, turbine blades).
Fiber-reinforced (metal matrix composite) superalloys	—	15 (matrix)	Turbine blades, vanes; combustor liners; cases
Monolithic ceramics	—	—	Turbine discs, vanes, blades, seals; cases; combustor liners
Ceramic-ceramic composites	—	—	Turbine vanes, blades, cases
Carbon-carbon composites	—	—	Combustor liners; cases; afterburners; nozzles; turbine discs, vanes, blades

KEY: HP = High pressure.
LP = Low pressure.
( ) = Less likely application.
— = Minimal or none.

SOURCE: Office of Technology Assessment.

Advanced Materials

There is currently a great deal of interest in the development of advanced materials such as rapid solidification processed materials, long-range order intermetallics, ceramics, and composites. This interest is driven by the impressive array of properties these new materials offer. They not only offer *enhanced* properties, but often entirely *new combinations* of properties, as well. A side benefit of advanced materials is their use of little or reduced amounts of strategic materials.

Many advanced materials are still undergoing R&D and have thus far seen limited commercialization. In selected component applications, some advanced materials are now being used. The number of applications for advanced materials should increase appreciably during the next 5 to 20 years—especially where major design modifications are not needed. In most critical applications where performance standards tend to be exacting, however, they will require much more R&D before they see widespread use.

Although growth in the use of advanced materials is expected, the overall effect of their use on future strategic material needs is unclear. Some major technical problems (e.g., the brittleness of ceramics, difficulties in repairing composites, etc.) must be solved before they can be used in many critical applications. Moreover, advanced materials will not necessarily be used as direct replacements for existing materials. In many applications, these new materials are so different from the alloy substitutes described previously that redesign of entire systems is often necessary to benefit fully from their properties. In addition, use of strategic materials may just as easily increase as decrease as these new materials are adopted. For example, using advanced materials in the hot section of a gas turbine engine to raise its operating temperature may increase the temperature in a cooler section of the engine to a point where it requires the use of strategic materials. Yet, using advanced materials (e.g., composites) to make an aircraft lighter may allow the use of smaller engines containing less amounts of strategic materials. In an economic sense, advanced materials and materials containing strategic elements may be both substitutes and complements.

The various industries involved in developing and producing advanced materials are doing so because of a belief in the promise of future economic benefit from the introduction of these materials in existing and entirely new applications, not because they foresee a role for them as materials substitutes. The advanced materials industry has the potential to make a large contribution to future U.S. gross national product (GNP). The U.S. market for advanced ceramic materials, for instance, has been projected at $5.9 billion by the year 2000, an amount 10 times the 1980 market.[25]

This emerging U.S. advanced materials industry faces global competition, especially from Japan and Western Europe, in materials development, processing, and commercialization. Today, some processed ceramic materials and components of composites are only available from foreign sources. In some instances, the United States is credited with the basic research on some material components for which Japan now holds most of the processing capacity. In others, process licensing has been made available to U.S. firms for foreign patented materials.

Compared to their metallic counterparts, advanced materials have relatively brief histories of use, and this absence of a proven track record often makes designers and their industries reluctant to use them. Different societies approach institutional barriers to commercialization in different ways. In the United States, the standard engineering education still provides little, if any, formal training in the use of advanced materials. Industry must bear the cost of continuing education. In Japan, industries are willing to introduce advanced materials to the marketplace at a lower level of confidence in their eventual success than in the United States. The risk of failure is reduced by testing new materials in everyday items such as scissors or high-value glamour products, such as sporting goods.

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[25] U.S. Department of Commerce, *A Competitive Assessment of the U.S. Advanced Ceramics Industry* (Washington, DC: U.S. Government Printing Office, March 1984), p. xiii.

The following sections present the current state of the art of these advanced materials, and, where known, potential areas for strategic material savings. It must be kept in mind, however, that many unknowns exist, and the rapid advance of the science of these materials could change their prospects in only a short time.

Ceramics

Advanced ceramic materials are an emerging technology with a very broad base of current and potential applications and an ever-growing list of material compositions (see table 7-9). While this dynamic situation makes it difficult to quantify their future impact, it does not appear that advanced ceramics will replace any substantial portion of the U.S. demand for first-tier strategic materials within the next decade. Beyond 2010, a larger potential for substitution exists if ceramic rotating parts are successfully applied in gas turbine engines. In order for this major materials substitution to be technically feasible, however, the brittleness tendency of ceramic materials must be overcome by improvements in material properties and processing technologies and the use of ceramics must be integrated with system designs that reduce the ways in which stresses are loaded on ceramic parts.

Most ceramic raw materials (see table 7-10) are not considered potential strategic materials because they are available in large quantities from domestic sources. However, the United States is competing with other countries in advanced ceramics R&D, and loss of a leadership role in the development and use of ceramic materials could ultimately result in a dependence on international sources (primarily Japan) for processed ceramic materials and products.

While a potential decrease in U.S. consumption of strategic materials is an important benefit of ceramic use, the promise of performance improvements is the main force driving the development of advanced ceramic materials. The sought-after properties of advanced ceramics include wear resistance, hardness, stiffness, corrosion resistance, and relatively low density (providing a weight savings that can translate into energy savings). A major attraction, however, is a high melting point and accompanying mechanical strength at high temperatures. Ceramics offer one of the best possibilities for raising the operating temperature of heat engines and power generating equipment; and as the operating temperature in these systems is increased, system efficiency in energy conversion can increase, resulting in cost savings. The metallic superalloys currently used in jet engines limit operating temperatures to about 2,000° F, whereas ceramic materials can withstand temperatures up to about 2,500° F. Complicated and energy-consuming cooling systems now must be used—even in relatively low-temperature engines such as automobiles—to maintain the integrity of metals at operating temperatures. Ceramic materials can also be used to increase the energy efficiency of many high-temperature processing systems. The excellent wear-resistance properties of ceramics could increase productivity in the machining, chemical, and metal processing industries, where wear and corrosion resistance are critical. Box 7-A provides detailed information on the properties of ceramics and on the processes for making them.

Although research into some areas of advanced ceramics is still in the development stages, new roles in electronics and wear-resistance applications are being filled by ceramics. Neither the economic viability nor the technical capability of using ceramics in many of the structural applications (e.g., heat engines) has yet been demonstrated. Although the basic ceramic raw materials (e.g., silicon, alumina, magnesium) are plentiful and inexpensive, the procedures necessary for converting the raw material into a usable form (usually an ultrafine powder) and then a final product can be expensive. It has been estimated that from 25

Table 7-9.—Current and Prospective Uses for Advanced Ceramics

Ceramic material	Current and potential applications	First-tier strategic materials substitution opportunities
Electric:		
Insulating (Al_2O_3, BeO, MgO)	IC circuit substrate, package, wiring substrate, resistor substrate, electronics interconnection substrate.	—
Low-firing and/or glass ceramics, ferroelectrics ($BaTiO_3$, $SrTiO_3$)	Ceramic capacitor.	Low-temperature firing permits use of copper instead of tungsten, moly or PGM wires, nickel instead of PGM electrodes.
Piezoelectric (PZT)	Vibrator, oscillator, filter, transducer, ultrasonic humidifier, piezoelectric spark generator.	—
Semiconductor ($BaTiO_3$, SiC, AnO-Bi_2O_3, V_2O_5, and other transition metal oxides)	NTC thermistor: temperature sensor, temperature compensation.	—
	PTC termistor: heater element, switch, temperature compensation.	—
	CTR thermistor: heat sensor element.	—
	Thick film thermistor: infrared sensor.	—
	Varistor: noise elimination, surge current absorber, lighting arrestor.	—
	Sintered CdS material: solar cell.	Pt, Pt-Rh heaters, Nichrome heaters
	SiC heater: electric furnace heater, miniature heater.	—
Ion conducting (β-Al_2O_3, ZrO_2)	Solid electrolyte for sodium battery.	—
	ZrO_2 ceramics: oxygen sensor, pH meter fuel cells.	
Magnetic:		
Soft ferrite	Magnetic recording head, temperature sensor.	Ceramics for Co-Sm magnets
Hard ferrite	Ferrite magnet, fractional horsepower motor, powders for tapes and discs (σ-Fe_2O_3, CrO_2).	Ceramics for AlNiCo magnets
Optical:		
Translucent alumina	High-pressure sodium vapor lamp.	—
Translucent magnesium oxides, mullite, etc.	For a lighting tube, special-purpose lamp, infrared transmission window materials.	—
Translucent Y_2O_3-ThO_2 ceramics	Laser material.	—
PLZT ceramics	Light memory element, video display and storage system, light modulation element light shutter, light value.	—
Chemical:		
Gas sensor (ZnO, Fe_2O_3, SnO_2)	Gas leakage alarm, automatic ventilation fan; hydrocarbon, fluorocarbon detectors.	Reduced use of Pt-group catalyst
Humidity sensor ($MgCr_2O_4$-TiO_2)	Cooking control element in microwave oven.	—
Catalyst carrier (cordierite)	Catalyst carrier for emission control.	—
Organic catalyst	Enzyme carrier, zeolites, other ceramics.	Catalytic processes may replace Co, Pt
Electrodes (titanates, sulfides, borides)	Electrowinning aluminum, photochemical processes, chlorine production.	—
Thermal:		
ZrO_2-based Al_2O_3-based Si-based	Infrared radiator, thermal barrier coatings.	Reduced use of W, Cr, Co, Ni

Table 7-9.—Current and Prospective Uses for Advanced Ceramics—Continued

Ceramic material	Current and potential applications	First-tier strategic materials substitution opportunities
Mechanical:		
Cutting tools (Al_2O_3, TiC, TiN, others)	Ceramic tool, sintered SBN. Cermet tool, artificial diamond. Nitride tool.	WC-Co cemented cutting tools and high-speed steels (Cr)
Wear resistant (Al_2O_3, ZrO_2)	Mechanical seal, ceramic liner, bearings, thread guide, pressure sensors.	Hard facing alloys (Cr, Co, Mn)
Heat resistant (SiC, Al_2O_3, Si_3N_4, ZrO_2, others)	Ceramic engine, turbine blade, heat exchangers, welding burner nozzle, high-frequency combustion crucibles.	Superalloys (Co, Cr)
Biological:		
Alumina ceramics implantation	Artificial tooth root, bone, and joint.	Bone and tooth implants (Pt, Co, Cr-based
Hydroxyapatite bioglass		

SOURCE: Elaine P. Rothman, George B. Kenney, and H. Kent Bowen, MIT Materials Processing Center, *Potential of Ceramic Materials to Replace Cobalt, Chromium, Manganese, and Platinum in Critical Applications*, OTA contract study, January 1984.

Table 7-10.—Some Advanced Ceramics Material Families

Families	Chemical formula	Elements
Alumina	Al_2O_3	Aluminum, oxygen
Aluminum silicate	AlSi	Aluminum, silicon
Barium titanate	$BaTiO_3$	Barium, titanium, oxygen
LAS		Lithium, aluminum, silicon
Magnesium silicate	MgSi	Magnesium, silicon
MAS (cordierite)	$2MgO \bullet 5SiO_2 \bullet 2Al_2O_3$	Magnesium, silicon, oxygen, aluminum
Magnesia	MgO	Magnesium, oxygen
Silicon carbide	SiC	Silicon, carbon
Silicon nitride	Si_3N_4	Silicon, nitrogen
SiAlON	(various alloys of silicon nitride and alumina)	
Zirconia	ZrO2	Zirconium, oxygen
PZT (partially stabilized zirconia)		Zirconia with particles of calcia, magnesia or yttria

SOURCE: Office of Technology Assessment.

to 75 percent of the production cost of ceramic components is due to a high rejection rate caused by the poor reproducibility of current processing steps.[28] As new manufacturing technologies mature and the ability to design with brittle materials increases, prices are projected to become competitive with existing metallic technologies. As yet, however, mass production of many advanced ceramics does not yet occur. Scaling up an experimental process to a commercial manufacturing level of production, while retaining the desired properties of the materials and obtaining production reliability, has not often been achieved.

Ceramics as a Strategic Material Substitute

A growing market for advanced ceramics exists in a number of applications, with limited implications for the use of strategic materials. Strategic material substitution, however, may have a higher potential in the long term (2010 and beyond), particularly in the eventual use of advanced ceramics in aircraft gas turbine engines and, to a lesser extent, as components in automotive gas turbine and heavy vehicle diesel engines.

As shown in table 7-11, ceramic materials are displacing some first-tier strategic materials in

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[28] Elaine P. Rothman, George B. Kenney, and H. Kent Bowen, Materials Processing Center, Massachusetts Institute of Technology, *Potential of Ceramic Materials to Replace Cobalt, Chromium, Manganese, and Platinum in Critical Applications*, OTA contract report, January 1984, p. 240.

Box 7-A.—Ceramics Primer

Ceramics, derived from the Greek word "keramos," meaning "burnt stuff," is a general term for inorganic,[27] nonmetallic materials processed or consolidated at high temperatures. Traditionally, ceramics has referred to the family of earthenware, brick, glass, porcelain, and enamels in common use. The field now encompasses a wide range of materials and applications.

Traditional types of ceramics are made from natural raw materials such as clay, silica, and feldspar and produced using relatively simple chemical processing, forming, and firing steps. Advanced ceramic products, on the other hand, are produced from ultrafine powder forms of synthetic materials derived from the natural raw minerals. The powder production phase of advanced ceramics processing has become increasingly critical. Purity, particle size, shape, and distribution of particles and how they agglomerate must be rigidly controlled in order to produce reliable, reproducible components. To attain such high-quality, new techniques such as sol-gel, coprecipitation, and laser synthesis have been added to conventional powder production and agglomeration methods.

Because a great number of materials are classified as ceramics, a wide range of properties are available; and ceramic materials have many characteristics that distinguish them from metals. They are generally more stable chemically and thermally and are better insulators than metals. On the other hand, they are much stronger in compression than in tension and do not have the same ductility, or "forgiving" nature, of metal. Ceramics are harder and more rigid than either metals or plastics and are more stable (retain their low-temperature properties) at high temperatures.

Owing to their lack of ductility, ceramic products cannot be formed by the stamping or forging processes used for metals. Instead, they are generally processed directly from highly refined raw material by the consolidation of powder. (Melt formation is used to form glass and single crystal ceramics.) The powder is first formed to the desired shape. Forming methods include isostatic pressing, injection molding, and slip casting. This "green body" preform is then further densified by the application of heat (sintering) or the simultaneous application of heat and pressure (two such processes are hot-pressing and hot-isostatic pressing). Reaction bonding and reaction sintering are special sintering processes during which the final composition of the ceramic material is obtained along with densification. The combination of processes selected to produce a ceramic material will affect its ultimate properties.

Ceramics are brittle and fracture with little or no warning. This characteristic has been the material's major barrier to expansion into a wide range of applications, both technically and institutionally. Ceramics must be considered and used in ways different from those taught traditionally to designers and engineers schooled in the use of metals. Because metals bend and deform prior to reaching a point of fracture, ceramics cannot usually be directly substituted for metal alloys on a one-for-one basis. Instead, redesign of components and systems to eliminate or minimize load-bearing (stresses) are often necessary in order to substitute a ceramic material.

A considerable amount of the research in ceramics centers around how to reduce, cope with, or design around this brittleness. Research takes three approaches: 1) basic research to increase the knowledge base and understanding of the behavior of the materials, 2) improvement of processing technologies to reduce the probability of brittle failure, and 3) investigation of how varying material compositions can affect ceramic properties.

Brittle failure results from microscopic flaws (cracks), solid inclusions, and voids in the microstructure[28] of finished products inevitably introduced to a ceramic material during processing. The likelihood of brittle failure increases with the size of such flaws, and tension loading on a part will lead to the

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[27] Substances that do not contain carbon except as a minor constituent.

[28] The detailed arrangement (size, nature, and distribution) of phases (combinations of elements) that constitute the overall material.

growth of existing flaws (crack propagation). New processing techniques aim at reducing flaw size and population by the use of homogeneous powders and forming procedures. Greater processing reproducibility is another goal.

Another, complementary method of decreasing the probability of fracture of ceramics is to increase the energy required to extend a crack in the material. Such a barrier to crack propagation is provided by introducing toughening mechanisms into the powders before processing. Examples include zirconium oxide particles embedded in aluminum oxide and calcia, magnesia, or yttria added to zirconia to create partially stabilized zirconia (PSZ).

The ability to identify the flaws can increase the reliability of ceramic products. Nondestructive evaluation (NDE) techniques are being developed (by both industry and the Federal Government) to determine flaw size, shape, concentration, and type with an aim toward predicting when component failure will occur. As yet, there is no "perfect" method for detecting all types of flaws in ceramics. Many methods are not applicable to the production line or are simply too costly and time-consuming. NDE techniques include ultrasonic, radiography, optical, and thermographic methods.

wear-resistant applications such as cutting tool tips, pump seals, bearings and nozzles, and in heat-resistant applications such as heat exchangers. Turbochargers with ceramic rotors may be offered by one Japanese automobile manufacturer within the next few years.

Wear-resistant parts today are often made from cemented tungsten carbide materials in which cobalt is used as a binder. This material accounts for 9 percent of the annual U.S. consumption of cobalt, more than half of which is estimated to be used in these wear-resistant applications. (Another major end use is machine dies.) In heat-resistant applications, ceramic materials such as silicon carbide, silicon nitride, and aluminum silicates can replace stainless steels and other heat-resistant alloys containing chromium, cobalt, and some manganese. While it is difficult to quantify the individual quantities of these metals used in wear- and heat-resistant applications, the overall amounts are thought to be small. The substitution of ceramic materials will, therefore, result in minor strategic material savings. Additional indirect savings may be generated by higher temperature operations, energy savings, and weight reductions made possible by the use of ceramics.

If successfully introduced in the rotor section of turbochargers, advanced ceramics will find their first commercial rotating, structural use and will replace nickel superalloys and nickel-iron alloys containing cobalt and chromium, respectively. With 100 percent penetration in the automotive market, ceramic materials would replace less than 1 percent of current U.S. cobalt and chromium annual consumption, but may inhibit a growing use of strategic materials.

Current automotive engines consume a negligible amount of first-tier strategic materials, but operating engine conditions require air pollution control devices that consume 1.5 percent of the chromium and 34 percent of the PGMs consumed annually in the United States. It has been suggested that the use of ceramic gas turbine and diesel automobile engine technologies may alter these pollutants, thereby changing the material requirements for catalytic converters. In aircraft gas turbine engines, on the other hand, a direct material substitution could occur with the replacement of superalloys containing cobalt and chromium currently consumed in portions of such engines. (The aviation industry annually consumes approximately 40 percent of the U.S. cobalt demand

Table 7-11.—Potential of Advanced Ceramics to Substitute for First-Tier Strategic Materials

Application	Current strategic material use estimated percent of annual U.S. consumption	Ceramic materials currently used or under consideration	Advantage to use of ceramics	Primary factors affecting adoption			Extent of current commercialization U.S. and world
				Technical	Economic	Institutional	
Near term (before 1995):							
Wear resistance:							
Cutting tool tips	Cobalt; as binder in tungsten carbide 5 percent	Alumina, silicon nitride, sialon	Increased productivity	Overcoming inadequate fracture toughness	Appears competitive with tungsten carbide	Most U.S. machine tools cannot accept ceramic bits. Lack of information within machine tool industry	2% of U.S. market. Higher in Japan and West Germany
Seals, bearings, nozzles, etc	Cobalt; as binder in tungsten carbide 3 percent	Alumina-zirconia, silicon carbide	Improved wear and corrosion resistance	No significant barriers	Competitive with tungsten carbide except large (>8 inch diameter seals)	Need to standardize parts. Consumer awareness and lack of desire to change; pumps are a replacement parts market, longer seal life is not seen as an advantage to producers	20% of U.S. and world market
Heat exchangers Large industrial Small single burner recuperators	Small amounts of chromium in high-temperature stainless steels	Silicon carbide Cordierite	Energy savings. Longer furnace life	Improved joining technology (ceramic/ceramic, ceramic/metal) and reproducibility of SiC tubes in processing	Higher initial capital investment than metallic heat exchangers. High cost of SiC tubing	Change over to electrical induction heating which does not use recuperators. Depressed state of the domestic steel industry and metal processing industries has inhibited change	<5% of U.S. market Possibly higher in Japan
Turbochargers (automotive)	Superalloys containing Chromium: (0.02 percent) Cobalt: (0.4 percent)	Silicon carbide, silicon nitride	Higher temperature capability with lower mass. Potential for lower costs	Overcoming difficulties in ceramic/metal joining; improving reproducibility of the ceramic rotors	Current cost of producing the ceramic rotor is high, but economies of scale are predicted	Ceramics will be used if they demonstrate superior performance	Expected limited introduction by Japanese soon; possible market penetration by 1990
Long term (after 1995):							
Automotive diesel engine (cylinder, pistons, sensors)	Some chromium and cobalt in heat resistant and specialty steels; in addition, chromium: 1.5 percent; PGMs 34 percent in automobile catalytic converters. (Use of ceramic parts will alter operating temperatures of engines, causing possible change in converter material requirements.)	Silicon, silicon carbide, silicon nitride, zirconia	Higher engine efficiencies potential. Lightweight engine components	Improved fracture toughness, reproducibility and reliability of parts	Only prototype parts are currently produced; generally, hot pressed prototype parts require diamond machining which is an expensive mass production technique. New processing techniques could generate significant economies of scale	Almost revolutionary change in engine style is required to fully realize ceramics potential	Only several demonstration engines so far
Automotive gas turbine combustors, shrouds, and rotors	(same as above)	Silicon carbide, silicon nitride, sialon, lithium, aluminum silicate	Higher engine efficiencies; ability to burn any fuel; lower mass. Potentially lower cost	Improved fracture toughness; thermal shock resistance; reproducibility and reliability	High cost of processing due to current techniques and limited production volumes	"Proof of concept" engines follow-on design will need thorough, exhaustive road testing to overcome brittle image of ceramics	Only prototypes and demonstration testing

NOTE: These applications are not meant to be all inclusive but represent key potential applications.

SOURCE: Elaine P. Rothman, George B. Kenney, and H. Kent Bowen, MIT Materials Processing Center, *Potential of Ceramic Materials to Replace Cobalt, Chromium, Manganese, and Platinum in Critical Applications*, OTA contract study, January 1984 and less than half a percent of its chromium demand, and most of this material is used in the manufacture of jet engines.)

Owing to their higher temperature capabilities, resistance to corrosive environments, low inertial mass, potentially low cost, and the ready availability of raw materials, ceramics could become an integral part of future power generating technologies. In contrast to current and near-term applications, however, major technical barriers must be overcome before ceramic components for diesel and gas turbine engines can advance from demonstration projects to commercialization. Improvements are needed in material properties (most significantly, fracture toughness), processing and fabrication techniques, ceramic-ceramic and ceramic-metal joining capabilities, testing procedures, and design methodologies. Ceramic components must be reliably produced and manufacturing processes must be capable of a high degree of reproducibility, neither of which is possible at the current state of the technology.

The Ceramics Market and Industry

The worldwide market for advanced ceramics in 1980 was estimated to be $4.25 billion.[29] Electronic components represent the primary market for ceramics, with cutting tools and wear parts second and third, respectively. Roughly half of the present overall demand is being met by Japanese companies, whose sales exceeded $2 billion in 1960.[30] While the electronic segment now accounts for more than two-thirds of the total market and offers significant growth potential, it may eventually be dwarfed by the ultimate size of the high-temperature applications market.

Indicative of a high level of uncertainty, projections made to estimate the value of the advanced ceramics market by 2000 vary widely. An American Ceramics Society study[31] projected a $20 billion world market, half of which would be domestic. The U.S. Department of Commerce was more conservative in a study released in 1984. It projected total domestic shipments (as equivalent to future market potential) of advanced ceramics of $5.9 billion. Included were electronics shipments of $3.5 billion; heat engines, $840 million; cutting tools, $960 million; and wear parts, $540 million.[32] In yet another estimate, advanced ceramic usage in automotive engines alone was projected to reach $30 billion on a worldwide basis by the year 2000.[33]

Except in electronics, advanced ceramic materials have penetrated a very small share of their recognized end use markets worldwide, primarily due to the state of the technology and relatively high costs of its products. While low-volume production adds to these high costs, demonstrated technical performance will not necessarily create markets for advanced ceramics. Roughly half of the cost of a typical ceramic component is estimated to be due to production rejects.[34] An incremental introduction into most markets is expected until ceramic component mass production techniques are developed which can reproducibly fabricate reliable products and customer acceptance can be firmly established. In automobile markets, revolutionary ceramic engine designs may have to await a lengthy proving process prior to successful commercialization. If it is successful, the ceramic turbocharger—the first commercial structural heat engine use of advanced ceramics—can provide invaluable information for this process and the beginnings of institutional acceptance of the structural capabilities of advanced ceramics.

The essence of the advanced ceramics business is that common starting materials are converted into high value-added commodities and components by sophisticated, high-technology processing and manufacturing systems. Exacting standards require extensive quality control. Generally, material producers in the ceramics industry have been and still remain vertically integrated; thus, raw materials are processed and fabricated into component parts within a single company. Relatively few producers supply ceramic raw materials, and even fewer supply new advanced ceramic powders. The evolving advanced ceramics industry consists of traditional ceramics firms expanding into new applications, new end users taking on the task of being materials suppliers, and conventional materials firms expanding into the ceramics arena.[35]

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[29] Rothman, et al., op. cit., p. 238.

[30] Ibid., Japanese firms were estimated to hold 52 percent of the worldwide ceramic powders market; 61 percent of electronic IC packages/substrates; 91 percent, piezoelectrics; 43 percent, capacitors; 63 percent, thermistor/varistors; 79 percent, ferrites; 11 percent, gas/humidity sensors; 44 percent, translucent ceramics; 12 percent, cutting tools (carbide, cermet); and 48 percent, structural ceramics (heat and wear resistant).

[31] Ibid.

[32] U.S. Department of Commerce., op. cit., p. 13. The Department of Commerce cautioned in its study that it is too early in the history of this new industry to predict its future with a high level of confidence.

[33] According to Kent Bowen of MIT, as quoted in Rothman, et al., op. cit.

[34] Ibid.

The United States is not alone in its interest in advanced ceramic materials. It already is competing with and will continue to encounter stiff competition from Japan and Western Europe in tapping future markets. The Japanese industry is currently the sole source for some high-grade ceramic powders (e.g., silicon carbide) and has eclipsed the rest of the world in supplying the electronics market.[36] A British firm, which holds numerous patents for sialons (a ceramic composed of oxides and nitrides of silicon and aluminum), now licenses others to manufacture these materials.

Japan began its comprehensive advanced ceramics R&D program only in 1977, but its government-industry-university collaborative effort is widely regarded as the best organized and financed in the world. The Japanese are, of course, more materials and energy import-dependent than the United States; and a prime goal of their research efforts is to ease that dependence. But they also view advanced ceramics as a technology which will be part of an industrial base for the future. In an issue of *The Japan Industrial & Technological Bulletin*[37] in 1983, R&D in ceramics is recognized as involving "huge investment risks" and requiring "a relatively long lead time before the commercialization of these materials." As such, the study concluded that the Japanese government "should take the main role in promoting advanced and fundamental reasearch as well as development." And, the primary objectives of the Fine Ceramics Office set up in July 1982 under the auspices of the Ministry of International Trade and Industry (MITI) are to "get a comprehensive picture of the domestic fine ceramics industry, systematize the industry, consolidate the industry's foundation and adopt comprehensive policies designed to promote the industry's sound growth."

While the United States, Japan and Western Europe have all followed interdisciplinary approaches in their independent research efforts, the U.S. effort has leaned toward basic research and design methodologies while others have emphasized materials supply and processing. As a consequence, some feel that the United States may end up lagging behind in the implementation and exploitation phases of advanced ceramics technology. In advanced ceramics (as in other new technologies), the Japanese seem willing to take the risk to apply state-of-the-art materials to consumer products. This provides field testing for improvement of the knowledge base of the technology, production experience and cost reductions, and income to finance further research efforts, all the while gaining customer acceptance for new materials.

If one assumes that the Japanese rather than the United States becomes the dominate factor in an all-important future automobile ceramic engine market, the United States could be adversely affected by a decline in the GNP, loss of employment opportunities, shift in the balance of trade, and loss of savings in energy costs.[38]

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[35] For a review of the status of the U.S. advanced ceramics industry and the firms involved, see the U.S. Department of Commerce, *A Competitive Assessment of the U.S. Advanced Ceramics Industry*, op. cit.

[36] Not all such sales in the United States are imports, however. Kyocera International, a subsidiary of Kyoto Ceramic Co. of Japan, established production facilities in San Diego in 1971 which now supply 70 percent of the U.S. demand for ceramic packaging for integrated circuits. See "The Japanese Score on a U.S. Fumble," *Fortune* magazine, June 1, 1981, pp. 68-72.

[37] Japan External Trade Organization, *The Japan Industrial & Technological Bulletin: The Development of Structural Fine Ceramics in Japan*, Special Issue, No. 15. 1983, pp. 6-7. Note that Japan uses the term "fine ceramics" for what is commonly referred to as "advanced ceramics" in the United States.

One aspect of the expanding ceramics industry for which there is little data is the possible environmental, health, and safety effects on the communities and workers where the processing occurs. While some may assume that these processes may be "cleaner" than those of existing metal production, the statistics as they are now collected and aggregated by the Environmental Protection Agency and the Occupational Safety and Health Administration based on the traditional ceramics industry do not correspond to the future industry.

Research in Ceramics Applications

Ceramics is an ancient art. Despite—or because of—the age old and common use of ceramics, it remained essentially an art until recently, when more exacting standards were asked of the materials. One major engineering textbook on ceramics states in its 1976 edition that:

> . . . until a decade or so ago, ceramics was in large part an empirical art. Users of ceramics procured their materials from one supplier and one particular plant of a supplier in order to maintain uniformity. Ceramics producers were reluctant to change any detail of their processing and manufacturing (some still are). The reason was that the complex systems being used were not sufficiently well known to allow the effects of changes to be predicted or understood, and to a considerable extent this remains true.[39]

British scientists conducted much of the original research in the 1950s and 1960s in ceramics theory, raw materials development, and processing methods. Not until the 1970s were ceramics developed to the point where they could be considered engineering materials in that their chemical and physical properties could be altered to match intended functions in various applications. This short period of development time probably contributes to the relatively low rate of usage of advanced ceramic materials so far.

Following is a discussion of the current status of the research and use of advanced ceramics in cutting tool, wear resistance, heat exchanger, and heat engine applications.

CUTTING TOOLS[40]

Cutting tool applications represent a limited but growing and potentially valuable market for ceramic materials. At present the total U.S. market for cutting tools has been estimated at $2.2 billion per year. Advanced ceramic cutting tools hold 2 to 3 percent of this market (compared to tungsten carbide at 45 percent).[41] Nine percent of the annual U.S. consumption of cobalt is used as a binder in tungsten carbide material.[42]

New cutting tools are continually being sought to increase manufacturing productivity by attaining higher cutting speeds and reducing the downtime of cutting machinery through improved lifetime of tool inserts. Ceramic materials have proven feasible in this application and may offer higher performance than existing cutting tool materials; but they must compete with new metal alloys, coatings, and processing methods (e.g., powder metallurgy) for market penetration. No one material meets all cutting requirements in all applications, and advanced ceramic cutting tools tend to be higher in cost than conventional tools,[43] owing to their smaller volume production and more complex processing. This higher initial cost, however, can be mitigated by the higher cutting speeds, if downtime due to lower reliability is not excessive.

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[38] L. R. Johnson, A. P. S. Teotia, and L. G. Hill, *A Structural Ceramic Research Program: A Preliminary Economic Analysis*. ANL/CNSV-38. Argonne National Laboratory, March 1983.

[39] W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2d ed. (New York: John Wiley & Sons, 1976), p. 1.

[40] Cutting tools are insert pieces—the cutting edge—held and guided by machine tools. The process of machine tooling shapes and removes excess materials from manufactured products to produce desired tolerances.

[41] U.S. Department of Commerce, op. cit., p. 35.

[42] Rothman, et al., op. cit., p. 168.

[43] According to an interim draft report (January 1984) by Charles River Associates for the National Bureau of Standards, *Technological and Economic Assessment of Advanced Ceramic Materials: A Case Study of Ceramic Cutting Tools*, a typical silicon nitride cutting tool is currently sold in the $18 to $20 range, whereas typical tungsten carbide cutting tools are priced at $4 to $5.

An increase in the use of advanced ceramics is dependent on improvements in ceramic materials and the machine tools in which they are used. Advanced ceramic materials have greater abrasion, wear, and creep resistance than their carbide counterparts, but less strength, fracture toughness, and thermal shock resistance. The attributes of ceramic materials provide superior performance at high cutting speeds (especially demanded by the automotive and aerospace industries), which can translate into productivity gains. But widespread conversion to advanced ceramic cutting tools will require investments in new machine tools as many of those still in use have neither the speed, power, nor rigidity needed to use ceramic cutting tools effectively.

While approximately two-thirds of current ceramic tool sales are alumina (Al_2O_3), introduced in the 1960s, the newest cutting tools in use today are based on the silicon family. (Silicon nitride exhibits twice the fracture toughness of alumina.) Rapid development of silicon nitride ceramics has been the result of accelerated research activity over the past decade on high-temperature structural ceramics for use in advanced energy conversion systems. Ford Motor Co., for instance, is now moving toward commercialization of its "S-8" material, which was developed during research on materials for gas turbine rotors.

Most of the direct research in cutting tools in the United States is conducted by private industry and has been estimated at $1 million per year.[44] Indirect benefits may accrue, however, from the much heavier investments by government, industry, and academia in structural ceramics R&D.

Japan and Western Europe are considered to be ahead of the United States in the development and utilization of ceramic cutting tools. (About half of the advanced ceramic tools sold in the United States are imported from Japan.) The difference in higher usage has been attributed to the fact that in the United States' older machine tool industry equipment is outdated and must be modernized or replaced before ceramic tools can be used to their full advantage.[45]

WEAR APPLICATIONS

Wear applications are often in low-temperature environments in which resistance to abrasion and corrosion are the primary performance goals. Applications include ball and roller bearings, valves and pipefitting, industrial fasteners, and pumping equipment such as seals, liners, and nozzles. The traditional materials for those applications are cemented tungsten carbide and wear-resistant steels (in which chromium is used as an alloying agent for its hardenability). Up to about 3 percent of U.S. cobalt consumption may be used in all wear-resistant applications and about 2 percent of chromium. Thus, strategic materials savings could result from more extensive substitution of ceramic materials in wear applications.

While the technical feasibility of wear parts made from ceramics (primarily aluminum oxides, and silicon carbides, silicon nitrides) has been demonstrated, the Department of Commerce has estimated that ceramics currently hold less than 1 percent of the annual $3.3 billion U.S. market.[46] The extent to which they will assume a greater share of these markets will be strongly affected by performance versus cost tradeoffs. The current state of processing and fabrication techniques for ceramic wear parts (rather than raw materials costs) leads to the higher initial costs than those for metal parts. Ceramics can, however, provide longer service life than metals.

The potential to resist fatigue, corrosion, high temperatures, and loss of lubrication better than metals make ceramic materials attractive for ball and roller bearing uses. Their high cost of fabrication, however, makes them impractical in many applications. Ceramic bearings tend to be consumed primarily by petroleum and chemical industries, which have demanding performance standards (e.g., in corrosive environments) and in specialized aerospace applications, all of which can absorb the high initial cost.[47] Pump seals are the largest wear application market now held by ceramics. The properties required are hardness, low friction, high resistance to corrosion, and high-temperature capability. Ceramics (especially, silicon carbide and silicon nitride) have been shown to be superior to metals in performance in this application and, with improved manufacturing techniques and reduced costs, are expected to assume more of the market. Nozzle parts must withstand high wear and abrasion resistance properties which the hardness of ceramics provides.[48]

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[44] Ibid., p. 45.

[45] E. Dow Whitney, "Process in Ceramics Research for Cutting Tools in the U.S., West Germany, Japan and Sweden," paper given at the National Science Foundation conference on *Substituting Non-Metallic Materials for Vulnerable Minerals*, June 1983, p. 1.

[46] Department of Commerce, op. cit., p. 35.

Research in wear applications for ceramics is primarily conducted by the private sector, much of which remains proprietary, resulting in little transfer of technology. The research is concentrated on improving the properties of the materials, on manufacturing techniques to reduce costs, and on nondestructive evaluation methods to gain reliability.

HEAT EXCHANGERS

Competitive pressure in high-temperature industrial processes, as well as the rising cost of energy and the reduced availability of high-grade fuels in the 1970s, have led to the development and expanded use of energy conservation devices such as heat exchangers.[49] As in other high-temperature applications, the use of advanced ceramic materials in heat exchanger technology allows for improved performance over metals and often makes the technology possible. In addition, ceramics can provide better oxidation and corrosion resistance, which can result in longer component lifetime. Constraints to the expanded use of ceramics in this application are those specific to individual types of heat exchangers, but include the need for improved materials properties such as thermal shock resistance and resistance to certain corrosive environments, the development of joining and sealing technologies, and low confidence in the reliability of the ceramic components. The use of ceramics is still not cost effective vis-a-vis metal alloys in some heat exchanger designs, especially for large industrial furnace and power systems, which are constructed from an array of thin-walled ceramic tubes. Processing technologies are still being refined to provide high reproducibility for long (greater than about 8 feet) tubes. In addition, sealing against leakage between the hot and cold streams has not been fully successful.

Because of their high temperature and often corrosive environments, heat exchangers have been predominantly fabricated from stainless steels and superalloys; therefore, substitution of ceramic materials will result in some savings of chromium and cobalt, although the amount is difficult to quantify due to lack of specific end use reporting. On the other hand, much recent heat exchanger technology has been made possible by new ceramic materials, and the resultant growth in the use of ceramic materials are not as replacement materials. The use of ceramic materials, such as high-temperature cordierite (a magnesium alumina silicate commonly refered to as "MAS"), silicon carbide, silicon nitride, aluminum oxide, and lithium-alumino-silicate (LAS) in this application will be driven by energy costs faced by users and the unit cost of fabricating ceramic components.

The use of ceramics in recuperators, a type of heat exchanger that allows a furnace to operate more efficiently by recycling its waste heat to preheat incoming combustion air, has received a considerable amount of attention. Both development and commercialization research in ceramic recuperators was contracted by DOE's Conservation Office through GTE Sylvania and the Carborundum Co. As a result, small ceramic recuperators are now commercially available and are economically viable. They can be retrofitted to existing furnaces with the modification of furnace burners to cope with the higher temperatures generated. The performance advantage of ceramic recuperators is expected to encourage their use in new furnaces and as add-ons to unrecuperated furnaces; but a changeover in large industrial systems will be slow owing to the high investment costs of such installations coupled with the current stabilization of energy costs. The GTE "Super Recuper" is reported to save some industrial furnaces 30 to 60 percent in fuel by enabling furnaces operating at 2,500° F to preheat incoming air to 1,600° F. Unlike the long tubular array systems, GTE's counterflow plate design heat exchanger does not present any major ceramics processing problems. But materials properties improvements are needed in order for the device to be applicable in certain highly corrosive environments such as those in the glass industry.

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[47] Ceramic bearings cost about $100 while similar steel bearings cost from $1 to $3.50.

[48] Rothman, et al., op. cit., p. 191.

[49] "Heat exchanger" is a generic term for any device that transfer heat from a fluid flowing on one side of a barrier to another fluid flowing on the other side of the barrier. Here, the term refers to the use of such devices in combination with industrial furnaces, stationary power generators, and engines.

A variety of other heat exchanger applications are being investigated by both the private sector and DOE. They include ceramic regenerator cores for inclusion in gas turbine engine designs and specific designs for use in cogeneration and combined-cycle power generation equipment.

HEAT ENGINES

Ceramic materials are under active investigation by both the Federal Government and industry for use in the propulsion of automobiles, trucks, military equipment (tanks and missiles), and aircraft as well as stationary uses, such as power-generating equipment. Research in these applications is being conducted to achieve significant advantages over the use of metal alloys, including fuel economy, improved performance, reduced maintenance, and possible reduction of pollution emissions, with savings of strategic materials a secondary objective.

Private sector R&D is focused primarily on advantages of ceramics that could translate into direct cost savings or improved product competitiveness. A review of the government-sponsored research in ceramic heat engines in table 7-11 shows that the main focus of that effort has concentrated on the gas turbine engine for automotive applications.

The ceramic materials being applied today to these technologies are generally termed "structural ceramics." They include monolithic forms of the silicon carbide (SiC), silicon nitride (Si_3N_4), zirconia (ZrO_2), and aluminum silicate (AlSi) families of ceramic materials. Ceramic composites are also being considered for engine applications because of their superior strength and hardness, low thermal expansion, and wear resistance, which may allow them to overcome the fracture problems of the monolithic ceramics. However, ceramic composites have been found to lose their strength at higher temperatures, a problem that has not yet been resolved.

Ceramics are likely to see service in the hot sections of engines, progressively, as follows:[50]

- Turbochargers: static parts and rotors.
- Small stationary electric power generators, similar to airplane auxiliary power units (APUs).
- Large stationary electric power generators, then mobile (ground and marine) APUs.
- Short-life turbojet and turbofan engines for missiles.
- Heavy-duty turboshaft vehicular propulsion engines; military truck, tank, off-road vehicular, marine engine.
- Automobile propulsion.
- Human-rated aircraft propulsion and utility electric power generation.

Technical advances gained from continuing research efforts are necessary before ceramic materials can serve in these applications.

VEHICLES

Ceramic materials are being considered either as direct substitutes for selected components of existing gasoline and diesel engines or for use in engines designed specifically to benefit from the properties of ceramic materials.

Component substitution in gasoline engines offers only minor improvements in fuel economy or power production over conventional all-metal engines. As such, while selected components (cylinder liners and heads, exhaust and intake ports, valves, bearings) of such engines may be fabricated from ceramics, a "ceramic gasoline engine" is not considered a possibility. Ceramic diesel engines, on the other hand, can provide a 10- to 30-percent reduction in fuel economy and improved reliability due to the elimination of cooling systems. Since only minor amounts of strategic materials are used in conventional engines, ceramic components substitution can only marginally affect the use of strategic materials. One possibility, as yet unproven, is that the pollutants emitted by such hybrid metal-ceramic engines will be lower, owing to higher operating temperatures, and that strategic materials savings could occur with a shift in the materials requirements (now, PGMs and chromium) consumed by automotive catalytic converter systems.

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[50] Parkinson, op. cit.

Turbochargers.—Turbocharger rotors, now made primarily of nickel-based superalloys and nickel-iron alloys, could be a significant near-term use of ceramics. This technology[51] is one of the few heat engine applications being investigated with mostly private rather than government funding and is driven by a desire to combine the fuel economy of today's small cars with the performance of yesterday's larger engines. As this competition for greater fuel economy/performance increases in the automotive industry, the inclusion of ceramic rotors in turbochargers may retard an otherwise growing market for superalloys. The main candidate material for ceramic rotors is silicon nitride.

The primary attraction of the ceramic rotor is the improved performance provided by its low rotational inertia, which enables a quick response by the turbocharger at low engine rpms. The higher weight of metal alloys causes a delayed response called turbo lag. Secondly, there are expected material cost savings to be gained from the use of ceramics, along with overall weight savings (providing additional fuel economy). The high-temperature characteristics of ceramics are not a prime factor.

Two technical problems constrain mass production of ceramic rotors for turbochargers: the difficulties in joining ceramics and metals and uncertain reliability and reproducibility in materials processing. Nevertheless, ceramic turbochargers may be offered—to a limited extent—by the Japanese automobile industry within the next few years. Two Japanese firms reportedly began delivering sample turbochargers to Japanese car companies in mid-1983 for testing purposes. One of these firms announced plans to begin production in late 1984 and predicted that its ceramic turbines will be mass-produced within 3 to 4 years. The major U.S. turbocharger manufacturer, Automotive Products Division of AiResearch, competes in international markets and expects to have its ceramic rotor turbocharger ready by 1986 for the 1987 model year. If the ceramic turborcharger is successfully marketed by the Japanese industry, the U.S. automobile industry is expected to compete by offering similar turbochargers on their specialty market automobiles, where such gains in performance are desirable and the consumer may be willing to absorb added costs (both initial and maintenance).

The ceramic turbocharger is seen as a precurser to the use of ceramics in gas turbine engines where the rotor must withstand higher stresses. Successful commercialization of the ceramic turbocharger could provide valuable information to accelerate the application of ceramics to gas turbine engines.

Gas Turbines and Diesel Engines.—Research in new automotive engine designs to incorporate ceramic materials has been a major beneficiary of government support. Technologies now being investigated under contract to industry are the "adiabatic" (or, minimum heat loss) diesel and gas turbine engines. Industry also supports R&D in engine technologies through cost sharing on government contracts and its own private basic research. While various government projects have been funded sporadically since the 1940s, the heaviest support has occurred during the last decade.[52] NASA was directly involved in the early research with the Department of Defense and the Department of Energy (DOE) now taking the lead. The current major projects are DOE's Automotive Gas Turbine (AGT) program to develop a gas turbine engine by fiscal year 1986 and the U.S. Army Tank Automotive Command (TACOM) program with Cummins Engine Co. to develop the adiabatic diesel engine for use in military vehicles. It is believed that this diesel engine technology will eventually be transferred to the private sector for use in heavy-duty trucks. Automotive use of both the diesel and the gas turbine engines, if commercialized, is not expected until after 2000.

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[51] A turbocharger, added to a standard internal combustion engine, pumps hot air (compressed by action of a turbine spun by hot exhaust gases) into the engine. Other options for fuel economy are available through redesign of the standard engine to improve its performance by reducing the amount of waste heat.

The benefits foreseen in use of the adiabatic diesel engine are increased fuel economy (due to the reduction of lost energy and the elimination of the need for a cooling system), reduction in weight and inertia, and greater engine reliability and maintainability. Energy loss may be reduced as much as 50 percent, and fuel consumption, 25 percent over conventional diesel engines with a significant increase in power.

The TACOM/Cummins research project started with development of ceramic components for conventional diesel engines. A second phase followed to design and test an uncooled, nonadiabatic diesel engine with ceramic and metal parts. R&D is now proceeding on an adiabatic diesel engine, combining both a ceramic combustion system and a turbocompound unit (to utilize waste heat). Remaining technical issues include the need for further materials research and the development of component manufacturing methods that are cost effective and provide reproducibility.

After Congress passed the Automotive Propulsion Research and Development Act (Title III of Public Law 95-238) in 1978, DOE and NASA initiated the AGT program. Two contracts were awarded: one to General Motors (Allison and Pontiac divisions) for the AGT 100 and another to the Garrett Corp. and the Ford Motor Co. for the AGT 101. Each of these contracts involve the design, development, and testing of an advanced ceramic automotive gas turbine engine. In the final versions the engines will have been designed from scratch to exploit fully the material properties of ceramics. Since its inception in 1980, the AGT program has been revised to take the development of the ceramic engine through to the proof-of-concept stage. A probable decrease in funding in fiscal year 1985 will require another shift in the overall program goals or organization.

Both the AGT 100 and 101 have successfully passed an initial testing phase. The models tested were designed using ceramics for static components, retaining metal for rotary parts. The phase now underway will test versions designed with ceramic rotary parts.

One of the largest technical problems foreseen with the application of ceramics as engine components is that of gaining reliability and reproducibility in the large-scale production that commercial automotive application will require. The ultimate phase required for bridging a tough attitudinal barrier ("ceramics are brittle") and to ensure transfer of this new engine technology will be to convince engineers, designers, the automobile industry management, and consumers that ceramics can indeed serve in these capacities. This will require rigorous testing of ceramic engines in real environments—in automobiles subjected to daily use over long periods of time.

Again, the benefits of strategic material savings from these new automobile engines will be minor except for the possible changes in materials now used for catalytic converters. Results from the use of advanced ceramic materials in vehicle applications and the knowl-

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[52] According to a draft interim report (November 1983) by Charles River Associates for the National Bureau of Standards, *Technological and Economic Assessment of Advanced Ceramic Materials: A Case Study of Ceramics in Heat Engine Applications*:

> Since 1976, total U.S. Government support for R&D in ceramic heat engines has exceeded $10 million per year. In 1981, 74 percent of total government funding was provided by DOE, 23 percent by DOD, and about 3 percent by NASA. In addition, Charles River Associates have estimated that private funding of structural ceramics R&D is roughly equal to the amount of funding received by the private sector from the government in this area. However, little information is available about the focus of this private funding, i.e., what amounts are devoted to heat engine applications.

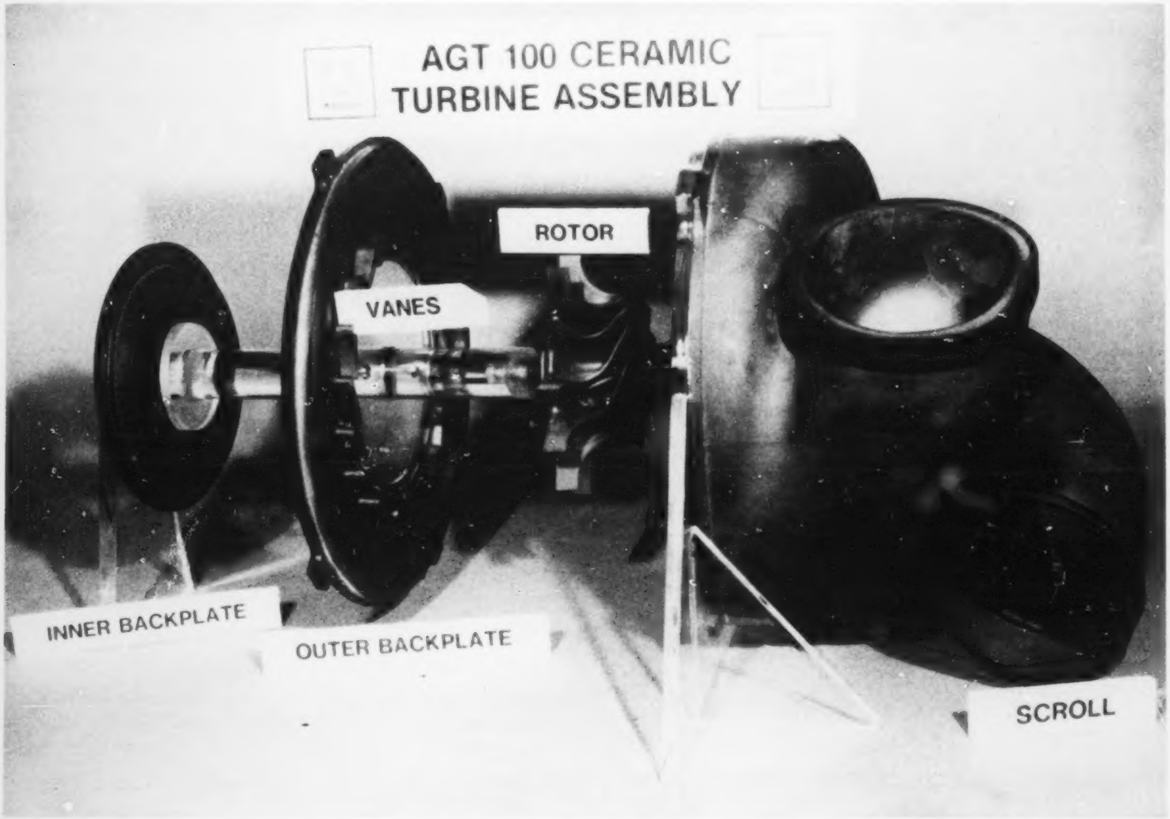

Photo credit: Allison Division, General Motors

Ceramic components are being evaluated in the advanced gas turbine being developed by Allison Division of General Motors for the U.S. Department of Energy and NASA

edge gained in processing of those materials will undoubtedly benefit the development of aircraft gas turbine engines, where real strategic materials savings may be realized from the substitution of ceramics for superalloys (chromium and, especially, cobalt).

AIRCRAFT TURBINE ENGINES

The use of ceramics in gas turbine engines for human-rated aircraft is believed to be one of the most challenging and difficult applications for advanced materials, owing to high performance demands and the extremely high risk of use involved. It is, however, an area in which the private sector is acutely interested because of a continuing desire to increase the performance of jet engines. This performance, which translates into fuel economies, increases as the inlet temperatures for a gas turbine engine increases. The current materials—superalloys—used in the hot sections of the engine have operating limits over time of about 1,950° F. Ceramics, on the other hand, can withstand operating temperatures up to about 2,500° F. This higher thermal efficiency allows for a reduction in airflow through the engine and a corresponding smaller engine size. NASA has estimated possible introduction of monolithic ceramics as turbine blades in this application around the year 2010.[53]

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[53] Parkinson, op. cit.

Both the Air Force and NASA[54] have maintained a continuing interest in ceramic gas turbine engine development. In the private sector, both Pratt & Whitney and General Electric Co. have contributed to basic research on structural ceramics for potential aircraft engine applications. The Air Force Materials Laboratory has sponsored small research programs on the evaluation of ceramics and ceramic composites with potential use in aircraft systems. NASA's Lewis Research Center, in addition to managing DOE's AGT programs, has sponsored small research programs on structural ceramics. NASA has also developed an overall program to augment its current research efforts in ceramics. This program, with its focus on the aircraft engine, is intended to broaden the technological base of advanced ceramics by coordinating research in the various technical needs (e.g., materials processing, nondestructive testing, design methodologies). The development of this plan was coordinated with other government agencies and industry but was not included in the final NASA fiscal year 1985 budget proposal.

Much work remains in developing monolithic ceramics and processing techniques and gaining applications experience before these materials will be acceptable for human-rated aircraft. The advantages of ceramics with regard to engine performance and, to a lesser extent, the potential for reducing the overall use of first-tier strategic materials are incentives that will help promote the still-substantial research, development, and commercialization tasks ahead.

STATIONARY ENGINES

Stationary engines being considered for ceramic materials applications are primarily gas turbines for industrial and household use, including accessory power units for emergency or peak load service. The possible development of these small generators for near-term use have benefited from research sponsored by DOE and the private sector. In the longer term, both General Electric Co. and Westinghouse are investigating the application of advanced ceramics in large gas turbines for electric powerplants. It is believed that the thermal efficiencies obtainable with the use of ceramics can result in considerable energy savings. To be economic, the ceramic materials will have to withstand long component lifetimes. These large units are not expected for use until 2000. Strategic materials savings could be realized through reduced use of wear- and corrosion-resistant materials, such as chromium alloy steels.

Composites

Two or more materials, when combined into a composite, can yield a product with very impressive properties, including high strength and stiffness, low weight, and good corrosion and chemical resistance. In addition, composites offer engineers unparalleled opportunities to tailor materials to particular applications. Most composites contain little or no strategic metals. As a result, the anticipated growing market for composites has the potential to displace some strategic metal use.

Technically, a composite is any material composed of two or more physically distinct phases. This category includes, among other materials, filled plastics, laminated materials, dispersion-strengthened alloys, and fiber-reinforced materials. Of these, the latter two are most likely to affect strategic materials usage. Dispersion-strengthened alloys were covered in the superalloy substitution section, so the discussion here will be limited to fiber-reinforced materials (commonly called advanced composites). The basic characteristics of fiber-reinforced composites are outlined in box 7-B.

Advanced composites can be made from several different combinations of matrix and reinforcement materials, but are generally classified by matrix material. Table 7-12 shows the most common matrix and filament combinations. Organic (polymeric) matrix composites (including fiberglass reinforcements) are the only composite materials in widespread com-

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[54] The budget for NASA's Ceramic Technology for Aerospace Heat Engines was an estimated $3.3 million in fiscal year 1983 and $4.4 million in fiscal year 1984.

Box 7-B.—Fiber-Reinforced Composites

Fiber-reinforced composites, which are continuous filaments or whiskers embedded in a binding matrix, exhibit properties that exceed those of its constituents taken alone. Each constituent serves a special function. The filaments provide the strength and stiffness, while the matrix provides the body of the finished composite product and transfers the stresses and loads to the fibers.

The mechanical properties of a composite depend on the composition of both the matrix and the fibers, the relative proportion of each, the orientation of the fibers, and the length of the fibers. By varying these parameters, the strength of a composite can be optimized for the loads encountered during its service.

The filaments, which account for 25 to 80 percent of the composite by weight, can be either continuous or discontinuous (whiskers). Composites with continuous fibers have outstanding directional properties, while those with discontinuous fibers lend themselves more readily to such conventional metalworking operations as forging, extrusion, squeeze casting, and welding.[55]

In addition to strength and stiffness, the filaments enhance other properties of the composite. Often, the filaments will increase the maximum service temperature by adding high-temperature strength to the composite. Also, certain filaments can enhance thermal stability because they do not expand greatly when heated (i.e., low coefficient of thermal expansion).

Since most of the load-bearing responsibility falls on the fibers, the importance of the strength characteristics of the matrix material is diminished. In fact, composites with the weaker, but lighter matrices such as plastics, carbon, and aluminum can have good strength. Therefore, composites are known to have good strength and stiffness for their weight (i.e., high specific strength and modulus).

The matrix provides more than the body of the composite. In unidirectional composites, which have all the filaments aligned in a single direction, the matrix provides most of the transverse (perpendicular to the fiber direction) and shear properties. Additionally, the matrix is responsible for much of the corrosion and oxidation resistance and for providing the visual and textural appearance of the finished composite product.

Although matrices and fibers serve different functions, they are not independent. The thermal expansion mismatch between matrix and fiber must be low to minimize thermal fatigue problems. Also, both phases must be chemically compatible at both fabricating and operating temperatures in order to prevent interdiffusion and the concomitant degradation of fiber strength. In some cases where such compatibility is inconvenient, barrier coatings can be applied to the fibers to inhibit interdiffusion.

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[55] Robert R. Irving, "Metal Matrix Composite Pose a Big Challenge to Conventional Alloys," *Iron Age*, Jan. 12, 1983, p. 35.

mercial use. Carbon/carbon composites are in limited production for aerospace applications. Metal and ceramic matrix composites have yet to be commercialized, except in highly specialized applications.

Prospects for composites to displace strategic materials varies by composite class. Organic or polymeric composites—the only composites now in widespread use—will seldom directly replace the first-tier strategic materials considered in this report, but the indirect effects of their use could be significant, as was brought out at a recent National Science Foundation workshop:

> It is unlikely that this country will witness any wholesale and direct substitution of composites for critical and strategic materials unless some national emergency dictates such steps. Rather, composite materials will make inroads in those areas where weight and/or cost are the primary drivers. Most of the critical materials, namely cobalt, chromium, platinum, tungsten and tantalum are used because of their unique resistance to high temperature,

Table 7-12.—Advanced Composite Materials Options

Matrix	Reinforcement										
	Carbon/graphite			S-glass	Aramid	Boron	Alumina	Silicon carbide	Quartz	Boron nitride	Tungsten
	Rayon Base	PAN Base	Pitch Base								
Organic											
Epoxy	⊗	⊗	X	⊗	⊗	⊗					
Phenolic	⊗	⊗							⊗		
Polyimide		⊗	X	⊗					⊗		
Bismaleimide		X									
Polysulfonate		X									
Carbon											
CVD	⊗	⊗	⊗								
Resin pyrolyzed	⊗	⊗	⊗								
Pitch pyrolyzed	⊗	⊗	X								
Metal											
Aluminum		X	X			X	X	X			
Magnesium			X				X	X			
Copper		X	X								
Lead		X					X				
Titanium						X		X			
Steel								X			X
Superalloys											X
Ceramic											
Silica									⊗		
Boron nitride										X	

NOTE: Circles indicate composites which have been or are now in production status.

SOURCE: Stanley L. Channon, *Industrial Base and Qualification of Composite Materials and Structures (An Executive Overview)* (Alexandria, VA: Institute for Defense Analyses, March 1984), working paper, p. 3.

corrosion or their catalytic phenomena. In no way can the composite materials we ordinarily consider, graphite, glass, or Kevlar with epoxy, polyimide, or thermoplastic resins be considered for direct substitution. The impact of composites will come indirectly in secondary effects. An example is a gas turbine in which the weight reduction by the use of composites for stationary, low-temperature components will cascade into downsizing of high-temperature components and result, not in elimination of the critical metals, but in a significant reduction in the amount of strategic material needed.[56]

Carbon/carbon composites, used primarily in aerospace applications, may also have indirect effects on strategic materials through redesign of products. Metal and ceramic/glass matrix composites may eventually be used in very high-temperature superalloy applications.

The high cost of advanced composite materials is an important deterrent to their widespread use. Table 7-13 shows the high relative raw material costs of various advanced composites. Moreover design, fabrication, testing, and inspection costs are often higher for composite materials than for monolithic materials. These costs can be expected to decrease as the materials come into more widespread use and as processing and fabrication problems are overcome. Figure 7-3 shows the decrease in graphite fiber costs since 1970.

The advanced composites industry has rapidly become internationalized, with the United States, Japan, Great Britain, France, and other countries participating in individual segments of the industry. Very often, separate fabrication steps needed in the manufacture of par-

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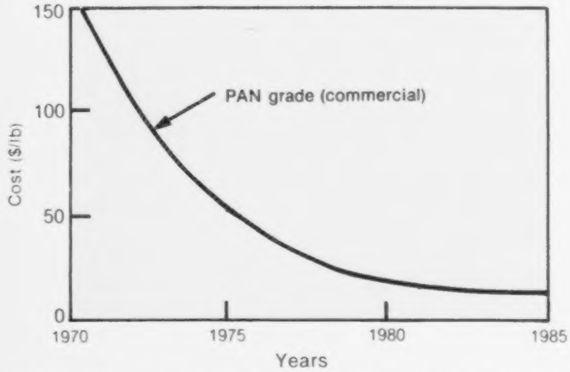
[56] William E. Winters, "Use of Composites in High Performance Structural Applications," *Materials and Society*, vol. 8, No. 2, 1984, p. 313.

Table 7-13.—Price Range of Selected Composite Raw Materials

Reinforcement	1985 cost/pound
Graphite grades:	
Rayon precursor fibers (woven cloth)	$70 to $80
PAN precursor (commercial and large-volume aerospace orders)	$17 to $40
Pitch grade (high-volume aerospace)	$35 to $275
Graphite fiber prepreg (PAN grade, 60 percent fiber)	$36 to $40; up to $100/lb for specialty products
Boron:	
Tungsten core	$365 to $375
Boron fiber prepreg (carbon core fiber):	
250° cure	$270 to $300
350° cure	$310 to $340
Kevlar:	
Type 29	$5.40 to $39.25
Type 49	$12.55 to $48.20

SOURCE: Various industrial producers contacted by the Office of Technology Assessment

Figure 7-3.—Graphite Fiber Cost



SOURCE: **1970-1980 data:** *Commercial Opportunities for Advanced Composites*, A. A. Watts (ed.) (Philadelphia, PA: American Society for Testing and Materials, 1980), publication 704, p. 90; **1985 data** provided by industry producers.

ticular composites are undertaken in separate countries. Although advanced composites are not strategic materials in the ordinary sense of the term, a growing concern in the defense community concerns U.S. dependency on foreign processing capacity to fabricate key composite components. Until recently, for example, the United States depended on Japan and Great Britain for virtually all carbon fiber reinforcements made from polyacrylonitrile (PAN), one of three possible precursor materials for carbon fiber. The United States now produces some carbon fiber using foreign PAN precursor materials. Also, Union Carbide has opened a domestic PAN production facility that reduces U.S. dependence on foreign PAN to 70 percent of domestic needs. However, this domestic precursor is not yet qualified for all defense programs, so in many critical applications dependence on foreign supplies is still near 100 percent. France, similarly, is the source of all quartz fibers and of an important curing agent used in epoxy resin formulations.[57] It has been estimated that, in most segments of the composites industry, U.S. production capability could be doubled within 2 years if the need arose.[58]

Polymer (Organic) Matrix

Polymers, such as polyesters, epoxies, and polyimides, are by far the most developed of all composite matrix materials. They are most frequently reinforced with (fiber) glass, graphite, or aramid (commonly referred to by its Dupont tradename, Kevlar) filaments. Polymeric composites can have performance capabilities that are commonly thought unattainable by plastics. For example, polyimide composites are capable of continuous operation at 700° F in some applications. Organic composites are attractive because they combine these good physical properties with lightweight and ease of fabrication. Consequently, these materials may reduce the need for strategic materials—not via direct substitution, but through the cascading effects of downsizing and redesign allowed by the decreased weight and innovative fabrication.

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[57] Stanley L. Channon, *Industrial Base and Qualification of Composite Materials and Structures (An Executive Overview)* (Alexandria, VA: Institute for Defense Analysis, March 1984), p. 10 (working paper).

[58] Ibid., p. 16.

The total U.S. consumption of polymer composites in 1982 approached 1 million metric tons (tonnes). Of this, 618,000 tonnes of polyester/glass (fiberglass) was the largest share. Additionally, 106,000 tonnes of reinforced thermoplastics and 28,000 tonnes of epoxy resins (equivalent to approximately 90,000 tonnes of epoxy-based composites) were consumed.[59] U.S. consumption of composite reinforcing filaments in 1982 was: glass, 280,000 tonnes; aramid, 900 tonnes; carbon (graphite), 800 tonnes; and other, 10 tonnes.

Fiberglass-reinforced organics (which are not generally considered advanced composites) dominate current markets. High-volume applications include boat hulls, plumbing and bathroom fixtures, and automotive body and trim panels, which are often made from polyester/glass composites. Low raw material costs and automated, high-speed production processes have made possible the widespread use of polyester/glass composites. Figure 7-4 shows selected applications for different fiberglass composites.

Because of their high price, use of other polymer composites has been largely limited to aerospace applications, sports equipment, and automotive applications. Low-volume aerospace applications for polymer composites have increased since 1968, when an epoxy/ boron horizontal stabilizer for the F-14 jet was first used on an experimental basis. In 1970, the Grumann Corp. approved this application for limited production.

Since then, air frames, air panels, satellite structures, and sporting goods have been built from advanced composites. Table 7-14 shows recent aerospace applications for advanced polymeric composites. In each of these applications, advanced composites were selected for their high specific properties. Specific properties refer to common materials properties (e.g., strength), normalized to the weight of the material. Organic composites have very good strength and stiffness for their weight and are therefore said to have high specific strength and stiffness.

Aside from polymer/glass composites, the polymeric composites with the greatest potential for continued growth appear to be epoxy/graphite and epoxy/aramid. Epoxy/boron (despite its early use) is no longer seen as promising, owing to difficulties in processing the extremely hard and brittle boron fibers, to high costs associated with producing the fibers, and to effective competition from the graphite and aramid systems.

Carbon Matrix

A carbon matrix reinforced with carbon or graphite fibers is commonly known as a carbon/carbon composite. They are high-cost materials used in specialty applications and are, for the most part, in early developmental stages. To date, commercial applications include rocket nozzles and exit cones, re-entry vehicle nosetips, and aircraft brakes.[60]

These materials are very strong and tough, and have the potential for maintaining these properties at temperatures up to 4,500° F. Moreover, carbon/carbon composites are very light—somewhat less than 25 percent of superalloy density and about 50 percent of ceramic (monolithic or ceramic/ceramic composite) density—dimensionally stable, wear resistant, and free of strategic metals.

There are, however, several disadvantages which must be addressed. Controlled environments or impervious coatings must be used to prevent oxidation problems in high-temperature applications, and special weaves of graphite fibers are needed to prevent surface fatigue cracking caused by low interlaminar strength.

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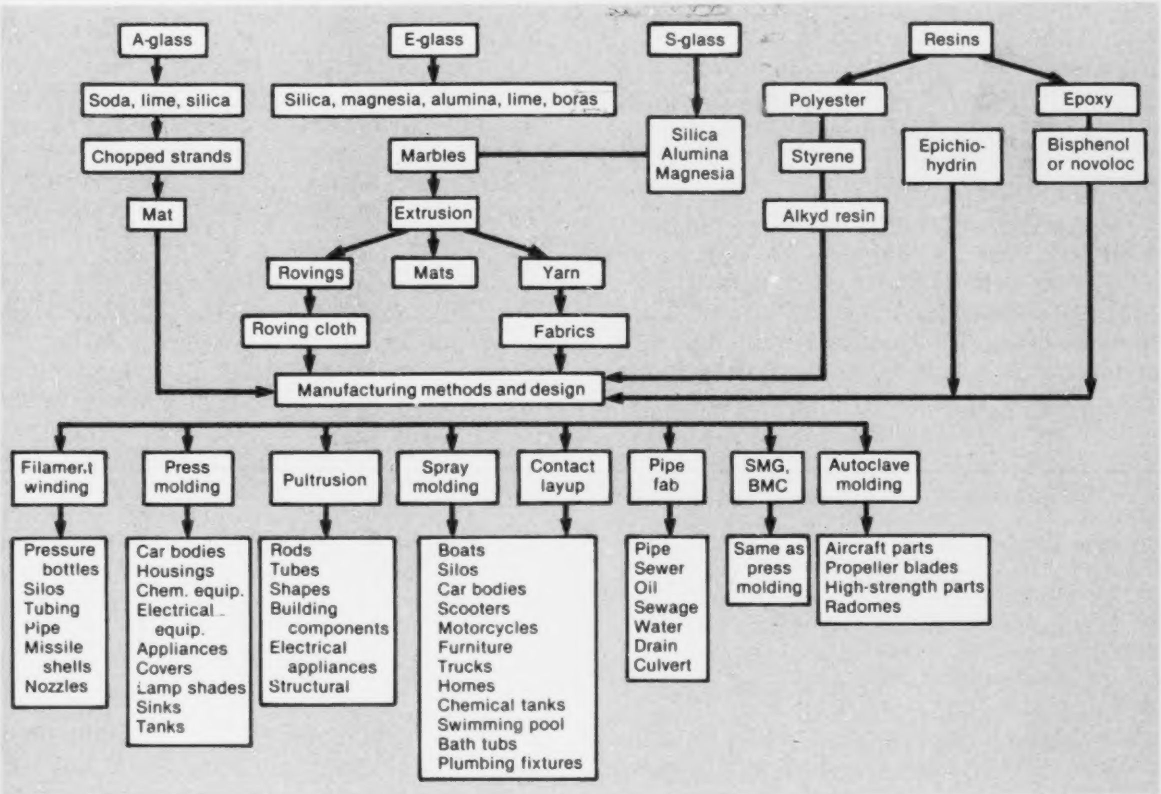
[59] Joel Clark, *Potential of Composite Materials to Replace Chromium, Cobalt, and Manganese in Critical Applications*, OTA contract report, 1984.

[60] Channon, op. cit., p. 36.

Figure 7-4.—Fiberglass Composite Applications


A-glass
E-glass
S-glass
Resins
Soda, lime, silica
Silica, magnesia, alumina, lime, boras
Polyester
Epoxy
Silica
Alumina
Magnesia
Chopped strands
Marbles
Styrene
Epichio-
hydrin
Bisphenol
or novoloc
Mat
Extrusion
Alkyd resin
Rovings
Mats
Yarn
Roving cloth
Fabrics
Manufacturing methods and design
Filament winding
Press molding
Pultrusion
Spray molding
Contact layup
Pipe fab
SMG, BMC
Autoclave molding
Pressure bottles
Silos
Tubing
Pipe
Missile shells
Nozzles
Car bodies
Housings
Chem. equip.
Electrical equip.
Appliances
Covers
Lamp shades
Sinks
Tanks
Rods
Tubes
Shapes
Building components
Electrical appliances
Structural
Boats
Silos
Car bodies
Scooters
Motorcycles
Furniture
Trucks
Homes
Chemical tanks
Swimming pool
Bath tubs
Plumbing fixtures
Pipe
Sewer
Oil
Sewage
Water
Drain
Culvert
Same as press molding
Aircraft parts
Propeller blades
High-strength parts
Radomes

SOURCE: *Commercial Opportunities for Advanced Composites*, A. A. Watts (ed.) (Philadelphia, PA: American Society for Testing and Materials, 1980), publication 704, p. 112.

In addition, carbon/carbon composites are very expensive as a result of the complex weaving procedures, long processing times, and high energy consumption involved in processing. As with most developing materials, the cost is expected to decrease as the technology emerges and production rates increase.

Development work at NASA and in industry is aimed at reducing the high fabrication costs of carbon/carbon composites. Improving composite strength and stiffness and increasing the reliability of coatings and oxidation-inhibiting matrix additives are also goals of this work.

U.S. carbon/carbon composite use is expected to grow rapidly, primarily because of defense and aerospace needs. In 1982, an estimated 200,000 pounds of carbon/carbon was consumed in the United States. One survey of government and industry experts found an expected need for 800,000 pounds of carbon/carbon by 1990—a quadrupling in demand in an 8-year period.[61] As already discussed, some concern exists about U.S. reliance on Japan for most of its carbon fibers made from PAN. Although rayon- and pitch-based carbon fibers exist, PAN-based fibers are used in most current applications. Figure 7-5 projects defense and civilian needs for carbon/carbon composites through 1990; this may be an overestimate, due to changed program priorities.

Ceramic/Glass Matrices

Monolithic ceramics and glasses are brittle and exhibit low fracture toughness. The toughness of these materials can be improved by

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[61] The 1982 estimate and the 1990 projection were made by Channon, op. cit., p. 42.

Table 7-14.—Current Aircraft Applications for Advanced Composite Materials

Component	Source	Remarks
Wing:		
F-15 composite wing	McDonnell Douglas	Graphite/epoxy used to form wing ribs and spars over much of the wing substructure; target weight savings for entire wing, 25%
C-5A leading edge slat	Lockheed-Georgia	Basic design is graphite/epoxy skins over aluminum honeycomb core: weight savings, 22%
F-5 main landing gear door	Northrop	Weight savings, 36%
737 spoilers	Boeing	Basic design is graphite/epoxy skins over aluminum honeycomb core with aluminum and fiberglass fittings, edgemembers and ribs: 108 units (27 ship sets) have been fabricated and service tested: weight savings, 15%
A-4 landing flap	McDonnell Douglas	Basic design is graphite/epoxy skins over aluminum honeycomb with aluminum edgemembers except for a molded graphite/epoxy actuator rib: weight savings, 47%
F-5 leading edge flap	Northrop	Weight savings, 32%
B-1 leading edge slat	Lockheed-Georgia	Basic design is graphite/epoxy skins over aluminum honeycomb core with aluminum and fiberglass ribs and trailing edge close-out. Front beam is molded graphite/epoxy along with the leading edge structure: weight savings, 15%; cost savings, 35%
Empennage:		
A-4 horizontal stabilizer	McDonnell Douglas	Basic design is multishear web/solid-laminate skin concept; shear web constructions are both graphite/epoxy laminates and fiberglass core-graphite/epoxy skin honeycomb structure: weight savings, 28%
F-5 horizontal stabilizer	Northrop	Basic design is graphite/epoxy skins over aluminum honeycomb core with aluminum close-out ribs, integral spar, and torque tube fitting: weight savings, 23%
F-4 rudder	McDonnell Douglas	Used graphite/polymide in leading edge spar; other high-temperature materials used were fiberglass olyimide honeycomb core, boron/polyimide prepreg. titanium, and high-temperature adhesive
DC-10 upper aft rudder	McDonnell Douglas	Graphite/epoxy rudder is 32 ft² rib-stiffened-skin design manufactured in a co-cured assembly; composite component weight is 57 lb: weight savings, 37%
L-1011 vertical fin	Lockheed	Graphite and Kevlar composite box beam and skins to replace 9 × 25 ft primary structure; composite component weight is 640 lb (17% metals): weight savings, 25%
Fuselage:		
A-7 speed brake	Vought Aeronautics	Built-up molded laminate design using graphite/epoxy elements bonded with structural adhesive: weight savings, 40%
F-5 speed brake	Northrop	Weight savings, 23%

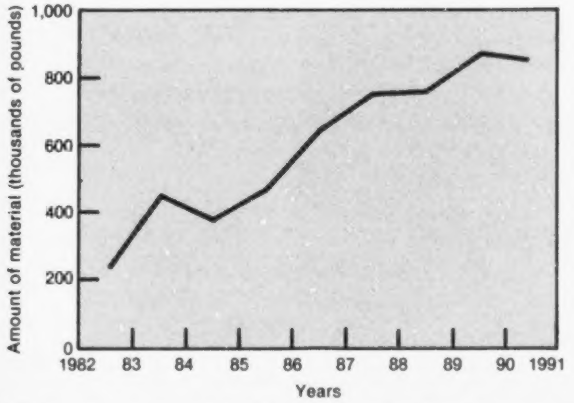
CONVERSION FACTORS: 1 ft² = 0.1 m²
1lb = 0.45 kg.
1ft = 0.3 m.

SOURCE: *Commercial Opportunities for Advanced Composites*, A. A. Watts (ed.) (Philadelphia, PA: American Society for Testing and Materials, 1980), publication 704, p. 104.

reinforcing them with ceramic fibers to limit the growth of cracks. Currently, glass matrix composites are more developed than their ceramic counterparts. Ceramic matrix composites are still confined to experimental applications—they are not currently used commercially.

Most glass compositions (e.g., lead, quartz, borosilicate, and boron oxide) have been reinforced on a laboratory scale. They have been allied with a variety of filaments, including alumina, silicon carbide, graphite, and tungsten, in order to improve their toughness and high-

Figure 7-5.—Carbon/Carbon Composite Needs[a]



[a] These estimates, reported in 1982, reflect anticipated use in weapons systems, aircraft brakes, and engines at that time. Recent changes in program planning indicate that these needs may be overestimated.

SOURCE: Stanley L. Channon, *Industrial Base and Qualification of Composite Materials and Structures (An Executive Overview)* (Alexandria, VA: Institute for Defense Analyses, March 1984), working paper, p. 43.

temperature strength. One promising example is United Technologies' lithium aluminum silicate glass, reinforced with silicon carbide fibers. This material has roughly 10 times the fracture toughness of the unreinforced glass up to about 2,000° F.

Ceramic matrices that have been examined experimentally include alumina, boron nitride, zirconia, silicon nitride, and silicon carbide. Reinforced with either inorganic materials or metal wires, these ceramics could possibly be used in applications with temperatures exceeding 3,000° F. As with glasses, ceramics are reinforced to improve their toughness. They do not, in general, benefit from any improvement in high-temperature properties.

Reinforcement of higher temperature ceramics has been relatively unsuccessful to date because of fiber strength losses due to fiber and matrix interaction at high fabrication temperatures, fiber recrystallization, and fiber fracture due to abrasion and stress during processing. As a result of these problems, NASA research has been redirected to ceramic composites employing weak bonding between the fiber and the matrix and to developing processing technologies that employ lower temperatures and no pressing. Clearly, ceramic/ceramic composites will need substantial additional research and development. They may eventually be used for turbine vanes, blades, and cases.

Metal Matrix

Metal matrix composites are relatively new structural materials. Many metals, including lead, titanium, stainless steel, magnesium, copper, nickel, and zinc, have been experimented with, but the most highly developed are aluminum matrix composites. Virtually any metal can be reinforced; benefits include increased specific strength compared to conventional metals, improved wear resistance, and higher allowable operating temperatures. However, the gains from reinforcement are often insignificant when compared with the costs.

Metal matrix composites are still primarily laboratory materials. However, some successful commercial applications exist. Toyota Motor Co. has developed an aluminum/alumina composite for reinforcing the piston ring groove in production diesel engines and is developing composite pistons and cylinder heads. In such applications, improved performance is highly valued, and this has been the justification for developing metal matrix composites. Table 7-15 shows some potential commercial applications of metal matrix composites.

Copper composites are under consideration for use in transmission lines. Lead is reinforced for use in batteries because in certain applications lead lacks the strength to support its own weight. Aluminum matrices, containing boron, alumina, or silicon carbide fibers are designed to compete with titanium. Reinforcing an aluminum alloy can raise its allowable service temperature by 200° F, permitting its utilization in many applications where it otherwise could not be used. Aluminum/graphite and aluminum/boron composites have been developed for use at 525° F.

Fiber-reinforced superalloy (FRS) technology is under development in the NASA Metal Matrix Composite Program. The aim of this program is to develop the technology to fabricate an FRS turbine blade capable of operating at a surface temperature of 1,100° to 1,200° C

Table 7-15.—Potential Commercial Applications of Metal Matrix Composites

Application	Desired properties	Suggested composite systems
Aerospace:		
Space structures	lightweight, stiffness	B/Al, B/Mg, Gr/Mg
Antennae	lightweight, stiffness	B/Al, B/Mg, Gr/Mg
Aircraft:		
Airplanes:		
Pylons	lightweight, stiffness, heat resistance	B/Al, SiC/Al
Struts	lightweight, stiffness, strength	B/Al, SiC^a/Al
Fairings	lightweight, stiffness	B/Al, SiC^a/Al, Gr/Al
Access doors	lightweight, stiffness, strength	B/Al, SiC^a/Al
Wing box	lightweight, stiffness, strength	B/Al, SiC^a/Al
Frames	lightweight, stiffness, strength	B/Al, SiC^a/Al, Gr/Al
Stiffeners	lightweight, stiffness, strength	B/Al, SiC^a/Al, Gr/Al
Floor beams	lightweight, stiffness, strength	B/Al, Sic^a/Al, Gr/Al
Fan and compressor blades	strength, stiffness, heat resistance, impact resistance	B/Al, SiC^a/Al, Gr/Al
Turbine blades	strength, stiffness, heat resistance, impact resistance	tungsten or tantalum fiber-reinforced superalloys
Turbine blades	strength, stiffness, heat resistance, erosion resistance	directionally solidified eutectics Ni_3Al-Ni_3Cb, Ni_3Al-Ni_3Cb-Ni, Ni-Mo wire
Helicopters:		
Transmission cases	lightweight, stiffness, strength	Al_2O_3/Mg, Gr/Al, Gr/Mg, Al_2O_3/Al
Truss structures	lightweight, strength, stiffness	B/Al, SiC^a/Al, Al_2O_3/Al
Swash plates	lightweight, strength, stiffness	Al_2O_3/Al, SiC^a/Al
Push rods	lightweight, stiffness, strength	SiC^a/Al, B/Al
Trailing edge of tail rotor blades	lightweight, stiffness, strength	Gr/Al, SiC^a/Al
Automotive:		
Engine blocks	lightweight, heat resistance, strength, stiffness	SiC^b/Al
Push rods	lightweight, heat resistance, strength, stiffness	SiC^a/Al, B/Al
Frames, springs	lightweight, strength, stiffness	SiC^b/Al
Piston rods	lightweight, strength, stiffness	SiC^b/Al
Battery plates	stiffness	Gr/Pb
Electrical:		
Motor brushes	electrical conductivity, wear resistance	Gr/Cu
Cable, electrical contacts	electrical conductivity, strength	Gr/Cu
Utility battery plates	stiffness, strength, corrosion resistance	Al_2O_3/Pb, Gr/Pb, fiberglass/Pb
Medical:		
X-ray tables, prosthetics	lightweight, stiffness, strength	B/Al,, SiC^a/Al
Wheelchairs	lightweight, stiffness, strength	B/Al, SiC^a/Al
Orthotics	lightweight, stiffness, strength	B/Al, SiC^a/Al
Sports Equipment:		
Tennis racquets	lightweight, stiffness, strength	B/Al, Gr/Al, SiC^b/Al
Ski poles	lightweight, stiffness, strength	B/Al, Gr/Al, SiC^b/AL
Skis	lightweight, stiffness, strength	B/Al, Gr/Al, SiC^b/AL
Fishing rods	lightweight, strength, flexibility	B/Al, Gr/Al, SiC^b/AL
Golf clubs	lightweight, strength, flexibility	B/Al, Gr/Al, SiC^b/AL
Bicycle frames	lightweight, strength, stiffness	B/Al, Gr/Al, SiC^b/AL
Motorcycle frames	lightweight, strength, stiffness	B/Al, Gr/Al, SiC^b/AL
Textile Industry:		
Shuttles	lightweight, wear resistance	B/Al, Gr/Al, SiC^a/AL
Other:		
Bearings	—	Gr/Pb
Chemical process equipment	—	Al_2O_3/Pb
Abrasive tools	—	B/Al_2O_3, SiC/Al_2O_3

[a] SIC whisker and/or continuous SIC filament.

[b] SIC whiskers only.

SOURCE: *Commercial Opportunities for Advanced Composites*, A. A. Watts (ed.) (Philadelphia, PA: American Society for Testing and Materials, 1980), publication 704, p. 119.

(2,000° to 2,200° F). FRS development has been carried out almost solely through NASA sponsorship. With no end user deeply committed to the material, its development pace has been slow.[62]

NASA's development prototype is a cobalt-free (15 percent chromium) iron-based tungsten fiber-reinforced superalloy (TFRS). This experimental material has been successfully fabricated into a turbine blade, but has not yet been engine tested. Cobalt- and nickel-based superalloys can be used as a matrix material, but only if a protective barrier is provided to prevent tungsten/matrix interdiffusion. Hence, the first FRS material likely to be commercialized will probably be cobalt free.

In addition to their high-temperature properties, TFRSs are good substrates for thermal barrier coatings (TBC), which also raise engine temperature capabilities. The thermal expansion coefficient of TFRSs is low compared to superalloys and approaches that of current TBC. Such coatings applied to TFRS components would, therefore, show less tendency to spall (i.e., crack and flake particles off the surface) than they do with present superalloys. (Spalling problems prevent TBC from being applied to present superalloy blade and vane air foils.) Further, regardless of the application of a TBC, the high thermal conductivity of TFRSs permits the use of simpler internal blade geometries for cooling air, thereby lowering manufacturing costs.

Several major technical problems currently limit the prospects for widespread use of TFRSs in turbines. The expansion coefficient of the tungsten fibers is approximately one-third that of the matrix. This induces thermal fatigue in a TFRS blade, considerably reducing its life. Also, tungsten fibers oxidize rapidly at turbine operating temperatures if exposed to the hot gas. Accidental exposure of the fibers in service could lead to rapid failure of the blade. At present, insufficient confidence exists that the probability of such exposure can be kept acceptably low, even with the application of a coating.

Ceramic whiskers and fibers also have been used to strengthen metal matrices. Such reinforcement is attractive because ceramic whiskers and fibers have high strength at ambient and elevated temperatures. high elastic modulus, good oxidation resistance, and low density. It has been found that ceramic reinforcement, usually as chopped fibers, can significantly improve the wear resistance of certain metals. However, results of research with both the whiskers and the long single crystal fibers have been disappointing so far.

One of the major advantages of metal composites over polymer composite systems is that there is not as large a difference between transverse and longitudinal strength. Transverse strength in metal composites is essentially equal to the strength of the matrix metal. An additional advantage, which can be important, is that metal matrix composites are electrically conductive.

Generally, the cost of metal composites is on the order of 10 times the cost of the matrix metal alone. Much of this differential is due to the high raw material cost of the reinforcement. Also, processing complexities add significantly to the total cost. For this reason, metal matrix composites are only considered for applications where the value of their added performance is great.

Prospects for the Future

Advanced composites are now entering a period of rapid growth. Much of this increased use will occur in the transportation industry, where there are significant incentives to decrease the weight and increase the performance of materials. Over the next 10 years, the aerospace industry could represent over 50 percent of the total high-performance composites market. Significant growth in the automobile and industrial sectors may occur in the late 1980s.[63]

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[62] Parkinson, op. cit.

[63] Clark, op. cit., p. 1.

Aerospace Applications

Most aircraft applications of composite materials do not require high-temperature performance and can be satisfied by polymer or aluminum matrix composites in such applications as airframe and structural parts. The use of aluminum matrix composites in these applications represents the largest foreseeable market for metal matrix composites. The downsizing and redesign, made possible through the reduction in weight, has the potential to reduce strategic materials usage.

Weight reduction in aircraft translates into fuel savings, lower operating costs, and increased profits for commercial aircraft; increased range, payload, and maneuverability for military aircraft; and reductions in manufacturing due to parts consolidation in both cases. The impetus for substitution of composite materials for conventional materials comes from market forces alone rather than from any desire to substitute strategic materials. Constant economic pressure can be expected to stimulate materials innovation.

Metal matrix composites, like advanced ceramics, ceramic composites, and carbon/carbon composites also have some potential for use in the jet engine industry, where the use of composite materials is expected to be performance- and market-driven. Cost considerations for jet engine materials will be of secondary importance relative to the overall cost of the engine.

While substantial technical problems must be overcome, these advanced materials could boost operating temperature above 2,500° F, far beyond even the most advanced superalloys now under development. However, use of these nonmetallic materials is not expected by NASA for human-rated engines until after the year 2010—roughly the same period as for advanced ceramics.

Tungsten fiber-reinforced superalloys will, in all likelihood, be used in jet engines only in the event of a prolonged crisis in the cobalt market. They have not satisfied important reliability criteria necessary for serious long-term consideration as substitutes for conventional superalloys or directionally solidified eutectics. They have not yet seen active operating service and would require a serious testing commitment before acquiring the confidence for industrial implementation.

Today, carbon/carbon composites can be fabricated into forms that may be useful in the gas turbine for combustor liners, cases, afterburners, and nozzles. A one-piece bladed turbine disc has also been formed. Industrial-research is at such an advanced stage for low- stress applications that jet engine afterburners made of composites could be in use in 5 years. High-stress applications are 10 or more years away. The complex qualification procedures used in the composites industry could affect timing, as well. These procedures are discussed in the concluding section of the chapter.

Carbon/carbon composites, despite their advantages in low-stress applications, cannot be expected to satisfy high-temperature, high-stress requirements for jet engine applications for another 10 to 20 years. Use of these materials will depend on developments in oxidation inhibitors and nondestructive testing methods. While materials prices are of negligible importance when compared to the overall cost of an engine, efficient implementation of these materials in jet engines will require a major overall redesign effort that will be both costly and risky. Industry seems to believe that government risk-sharing will be necessary to promote a rapid development of these novel technologies.

It is not expected that engine blades will be made of carbon/carbon composite materials, if only because reliability criteria for rotating high-stress parts are far from met, and testing has been far from sufficient.[64]

Automotive Applications

Currently, all the major automotive manufacturers have active development programs investigating the use of advanced composites in automotive structures. A wide variety of prototypes have been fabricated of advanced composites, including hinges, brackets, leaf springs, drive shafts, doors, and door guard beams. Many of these components have been tested in actual service over the last few years and have been found to perform well. Composite parts equivalent to steel parts in performance have been built. Significant redesign of these components has been accomplished to take advantage of the design flexibility which composites offer. Table 7-16 shows the potential automotive applications for Kevlar-reinforced composites.

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[64] Clark, op. cit., p. 75.

Composites will also see increased use in automobile engines. Toyota has used aluminum reinforced with polycrystalline aluminum oxide fibers for the connecting rods in an experimental engine. Advantages of composite use in engines could include increased fuel efficiency, faster engine response, and reduced engine vibration.[65]

Large-scale use of composites by the automotive industry could occur as broader consumer acceptance, lower production costs, and design concepts lead to a general expansion of composite materials markets and lower prices. Corporate Average Fuel Economy (CAFE) regulations have been instrumental in creating an environment for novel new concepts of automotive designs and materials usage. However, these pressures have been relieved by automotive downsizing to meet CAFE standards in the short run. If CAFE requirements become more stringent and make downsizing less profitable in the U.S. market, polymeric and metal matrix composites could be a very important means of achieving weight reduction. New auto body parts production and assembly technologies, which are likely to affect the use of composites in automotive structures, are expected to see implementation over the next 10 years. Use of composites in substantial quantities is not expected to increase before the 1990s. The impact of composites technology on critical materials (mostly chromium) will be largely indirect, through weight reduction and performance enhancement.

Table 7-16.—Potential Automotive Applications for Composites of Kevlar 49 Aramid

Potential application	Reasons for use
Leaf springs	reduced weight, stiffness, fatigue resistance
Transmission supports	reduced weight, stiffness, vibration damping
Drive shafts	reduced weight, stiffness, fatigue strength
Bumper beams	reduced weight, stiffness, damage resistance
Radiator supports	reduced weight, stiffness
Anti-intrusion beams	reduced weight, damage resistance
Wheels	reduced weight, damage resistance
Body parts	reduced weight, stiffness, damage resistance
Clutch faces, brake linings	strength, wear resistance, high temperature, frictional properties

SOURCE: *Commercial Opportunities for Advanced Composites*, A. A. Watts (ed.) (Philadelphia, PA: American Society for Testing and Materials, 1980), publication 704, p. 119.

Barriers to the Adoption of Composites

Composites have some major technical problems which counter the attractiveness of many of the properties described above and inhibit the introduction and effective use of these materials. There is little doubt that many of these problems will be overcome as the technology matures.

Use of composites in many potential applications has been discouraged by the lack of established design practices and insufficient design data. Additionally, when composites are selected for use, they are often used as direct substitutes for conventional materials without redesign. The performance of composites in such circumstances is often less than optimal. The implementation of sophisticated computer-aided design algorithms promises to reduce greatly the complexity of designing for composite structures and allow more effective use of composites.

Another problem of composites is the high cost of raw materials, especially high-performance reinforcements such as boron, graphite, and aramid. Prices for these reinforcements range from $20 per pound to well over $100 per pound. For this reason, advanced composites (those with specific properties exceeding steel) are selected only for applications where their special properties are highly valued.

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[65] *Metal Progress*, February 1984, p. 14.

Contributing to the high cost is the poor productivity of composite product fabrication. Processing composites is generally labor-intensive and time-consuming. While innovative techniques for automated, high-speed processing have been developed, their use is not widespread and is usually limited to forming specific types of goods. Moreover, once a nonmetallic composite is fabricated, the integrity of the structure is difficult to assess without destroying the component. This drawback is being overcome with the advent of nondestructive tests based on ultrasound and laser holography and with improved design procedures and increased experience in end uses.

Long-Range Order Intermetallic Materials

Materials in which two elements are arranged in an ordered pattern throughout the entire crystal lattice are known as long-range order intermetallics. Although there are many types of intermetallics, three families are particularly interesting with respect to the use of strategic materials:

Nickel aluminides	NiAl and Ni_3Al
Titanium aluminides	TiAl and Ti_3Al
Iron aluminides	FeAl and Fe_3Al

None of the above materials contains any cobalt or chromium, but other compounds could contain strategic materials. Very little information concerning long-range order materials is publicly available, making it difficult to assess the state of the technology or determine when it will be commercialized.

Each of these six materials has low density as well as excellent high-temperature stability, strength, and oxidation resistance. These properties have been known for many years, but the materials have seen little service because of brittleness problems. Their poor ductility, particularly at low temperatures, results in fabrication problems, low impact strength, and low thermal shock resistance. Recent research, however, has shown that the ductility can be improved by microalloying and thermomechanical treatment. This raises the prospect of using the intermetallics in high-temperature applications, such as gas turbines, where strategic materials are currently used.

Nickel Aluminides

Single crystals of Ni_3Al exhibit good ductility, but polycrystalline Ni_3Al is very brittle. Because of the cost and inconvenience of single crystal-technology, monolithic Ni_3Al is unattractive for most applications.[66] Research at Oak Ridge National Laboratory has demonstrated that small additions of boron (around 0.05 percent) to the polycrystalline form removes the ductility problem.[67] Microalloying (doping) with boron makes it possible to extrude, forge, and cold roll these materials. In addition to being fabricable, these boron-doped aluminides have tensile strengths that compare favorably with those of Waspaloy, Hastelloy X, and 316 stainless steel.

Possessing high-temperature strength and oxidation resistance, and adequate ductility and fabricability, boron-doped Ni_3Al alloys have potential as structural materials. The aircraft gas turbine industry is beginning to evaluate the material for various applications. Polycrystalline forms are being considered for discs—operating temperatures up to 1,250° C, or 2,280° F, seem possible. Combustor liners and turbine vanes are other possible uses. A single crystal Ni_3Al turbine blade is also of interest.

The good oxidation resistance of Ni_3Al results from the formation of aluminum oxide scales, which protect the alloy. Recent work has shown that alumina-forming materials have excellent hot-corrosion resistance in coal energy conversion systems. Such findings suggest that aluminides may be useful as structural materials in sulfiding environments.

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[66] Ni_3Al is most commonly known as the dispersion phase (gamma prime) that imparts high-temperature strength to nickel-based and iron-nickel-based superalloys.

[67] C. T. Liu and C. C. Koch, "Development of Ductile Polycrystalline Ni_3Al for High-Temperature Applications," *Technical Aspects of Critical Materials Use by the Steel Industry, Volume IIB*, NBSIR 83-2679-2, June 1983, op. cit.

Titanium Aluminides

The ductility problems of Ti_3Al are overcome by microalloying with columbium (niobium), a second-tier strategic material. Ti_3Al is being studied in the United States for use in aircraft gas turbine engine compressor rotors and blades and in low-pressure turbine discs, blades, and vanes. These materials are potential (albeit expensive) substitutes for some superalloys (e.g., Waspaloy and Inco 713.)[68]

Iron Aluminides

Pratt & Whitney Aircraft has studied these materials in conjunction with rapid solidification rate processing.[69] The inherent ductility problem was removed and an increase in tensile strength achieved by microalloying with titanium diboride (TiB_2). The particular interest in these materials is for use as sheet for combustor liners—up to temperatures of 1,800° to 2,000° F. Iron aluminides are also of interest for turbine discs, blades, and vanes at lower temperatures, and for cases.

Nickel, titanium, and iron aluminides are all in relatively early stages of development. While they have shown great promise to date, much remains to be learned concerning the full range of their material properties.

Rapid Solidification

Many new and potentially useful materials are being developed using technologies that solidify molten alloys extremely quickly. These rapid solidification (RS) technologies enable materials engineers to improve current alloys and to explore previously unattainable alloy compositions and microstructures. The effects of this new technology on the use of strategic materials are as yet unknown. As emphasized in a 1983 NMAB study:

> Work is continuing in the field of rapid solidification and its applicability to the reduction of strategic elements. Work to date indicates that this method of processing holds much promise for attaining at least a degree of independence from such elements as cobalt and chromium in various systems of alloys. However, it must again be emphasized that, for critical alloy applications, the principal motivation in alloy and process development is the achievement of improved mechanical, physical, or chemical properties. Whether the successful application of RS technologies will be accompanied by a reduction of the use of strategic elements cannot be foreseen at this time.[70]

Rapid solidification refers to the chilling of molten materials into solids at very high cooling rates. Materials are considered rapidly solidified when they have been cooled fast enough to assume microstructures that cannot be generated by conventional solidification techniques. Cooling rates obtained with RS processes are often on the order of millions of degrees Celsius per second.

Because of the heat transfer characteristics needed to attain the requisite high cooling rates, RS materials must have high surface area-to-volume geometries. This requirement limits the shapes of RS products to powders, flakes, and ribbons. These are rarely used in the as-cast form; usually, consolidation and mill working operations are needed. The casting, consolidation, and mill working processes are described in box 7-C.

RS in Strategic Materials Substitution

A vast number of alloy systems have been rapidly solidified in the course of scientific inquiry, but commercial interest in RS has been limited to only a few classes of alloys. Of these, transition metal-based glasses and aluminum-, nickel-, and iron-based crystalline alloys seem to have the greatest commercial potential.[71] In

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[68] Parkinson, op. cit., p. 49.

[69] Joseph Moore and Colin Adam, "Potential of Rapid Solidification for Reduction of Critical Element Content of Jet Engine Components," *Conservation and Substitution Technology for Critical Materials, Vol. II*, NBSIR 82-2495 (Springfield, VA: National Technical Information Service, April 1982).

[70] NMAB-406, op. cit., p. 68.

[71] J. V. Woods, "Rapid Solidification Processes and Perspective Part II," *Materials and Design*, vol. 4, April/May 1983, p. 712.

Box 7-C.—Rapid Solidification Technologies

Several methods have been devised to achieve the high cooling rates associated with rapid solidification. In all of them, molten metal is quenched at rates varying anywhere from 10^3 to 10^7 degrees Celsius per second. The powder, flake, or ribbon produced by these methods can be either crystalline or amorphous, depending on the alloy compositions and cooling rates used. Other parameters affecting the viability of the various processes include: the sizes, shapes, distribution, and handling characteristics (cost, safety, cleanliness) of the particulates, the production rates, and the production mode (batch or continuous).

A number of processes involve breaking up liquid alloy streams into molten droplets, with subsequent solidification of these droplets in flight. Among these processes are: gas or air atomization, ultrasonic atomization, rapid solidification rate process (centrifugal atomization), rotating electrode process, and soluble gas process. The quench rate can be increased appreciably by allowing the molten metal to impinge directly on a cooled substrate. The substrate quenching methods include: spray rolling, double roll quenching, melt extraction, transmet flaking, and self-substrate cooling.

Once a mix of metal and alloy powder is rapidly solidified, it is usually consolidated into a billet and then rolled, machined, extruded, forged, or otherwise mechanically shaped. As a first step, the particulate is densified by vibratory packing and by mechanical cold or hot compacting. This compact is then preheated in a vacuum to remove most of the surface oxides and hydrates formed during particulate production, storing, and handling. Following the preheat, the compact is further consolidated, by either mechanical hot pressing or hot isostatic pressing, to increase density prior to hot working in mill operations. Because these processes rely partially on heat to induce densification, they can be damaging to the RS microstructures. These problems can be avoided with dynamic compaction processes which use explosives or high-velocity projectiles to effect consolidation. More development work is needed, but dynamic compaction is a promising method of consolidating RS powders.

The principal mill product processes include sheet and plate rolling, extrusion, and forging. Secondary processes may involve operations such as rod and wire drawing, swaging, and tube drawing. Process parameters such as temperature, percent reduction, and forming rate must be established and controlled in a way that minimizes grain and inclusion growth and phase separation, which deteriorate the desired properties, but this is not likely to require the development of new technology.

Direct powder-to-hot-work processes could be used if the surface oxides and hydrates formed during particulate production and handling could be suppressed. If this becomes possible, much of the consolidation stage may be eliminated, thus leading to optimum process simplification and minimum cost. Except for the Reynolds Aluminum direct sheet rolling production program, the work in this area is still experimental.

general, glassy materials are most interesting for their magnetic or electrical properties, while crystalline alloys are of interest for structural applications. Some of the potential applications of RS materials include:

Aluminum alloys for aerospace structures. RS aluminum would compete with polymeric- and, possibly, aluminum-matrix composites and titanium in these applications.[72] [73]

Nickel alloys with abnormally high refractory metal concentrations for gas turbines.

Steels with submicron-sized phase dispersions for higher speed bearings.

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[72] National Materials Advisory Board, *Rapidly Solidified (RS) Aluminum Alloys—Status and Prospects*, National Research Council, Publication NMAB-368 (Washington, DC: National Academy Press, 1981). This unclassified document contains information which is subject to special export controls. It should not be transferred to foreign nationals in the U.S. or abroad without a validated export license. Distribution is limited to U.S. Government organizations. Other requests for the document must be referred to DARPA/TIO, 1400 Wilson Blvd., Arlington, VA 27709.

[73] C. Blankenship, Panel/Workshop on Critical Questions in Rapid Solidification Processing, *Rapid Solidification Processing, Principles and Technologies, III*, Proceedings of the Third International Conference on Rapid Solidification, Reston, VA, 1983.

> Amorphous (glassy) eutectic iron alloys with unusual electrical and magnetic properties for power transformers and magnetic applications. Use of RS alloys with good magnetic permeability coupled with high resistivity can cut transformer core losses by 60-70 percent. This can greatly reduce energy wastage during power distribution.[74] [75]

Commercial use of RS is still limited primarily for cost reasons. Auto industry experts estimate it will be 10 to 15 years before the technology reaches their area. Entry should be sooner in aerospace where a 10-percent improvement in strength-to-weight ratio warrants a twofold to threefold increase in raw material price.[76] Based on information gathered at the first Workshop on Rapid Solidification Technology held at the National Bureau of Standards (NBS) in 1981, the NMAB concluded that:

> The primary application of RS crystalline alloys at this time are superalloy disks for aircraft engines and high speed tool steels . . . and near-term opportunities for commercial applications of RS aluminum alloys appear limited to the aerospace industry.[77]

Limited commercial acceptance notwithstanding, RS research enjoys substantial support from industry. Pratt & Whitney Aircraft, with the considerable support of the Defense Advanced Research Projects Agency (DARPA), has played a major role in promoting RS alloy development. Production of RS superalloy material has reached the level of a few thousand pounds per year and some discs made from RS material have been incorporated into jet engines.[78] [79] If processing difficulties can be overcome, it is possible that the suitability of different RS alloys for other engine applications could be determined in 5 years (with an expenditure of $5 million for each application).[80]

Cobalt-free superalloy powders produced through various rapid solidification processes have been shown in early experiments to have some advantages over conventionally processed alloys. One promising example is an experimental, cobalt-free superalloy being developed by Pratt & Whitney Aircraft for turbine airfoils. The alloy, which chiefly contains nickel, molybdenum, and aluminum, offers superior creep resistance compared to some other hot-section alloys. Moreover, with addition of 3 percent chromium as well as smaller amounts of hafnium and yttrium, the RS alloy has oxidation resistance exceeding that of alloy 454 (10 percent chromium), now used in the turbine blades of the F-100 jet engine. The RS alloy "offers approximately 150° F advantage in temperature capability over our current (directionally solidified polycrystalline) metals in the stress range critical for blade design."[81] Depending on the design strategy, the increased temperature capability can be used to improve the performance, durability, or cost of the engine. R&D with this RS superalloy continues, but neither the results nor an estimate of the possible year of introduction are available.[82]

The development of rapidly solidified iron-based alloys has received support from DARPA and the Army Materials and Mechanics Research Center (AMMRC). These two organizations have sponsored a program at Marko Materials Inc. aimed at developing RS iron-based alloys for potential high-temperature structural applications in the intermediate temperature range of 800° to 1,200° F. These new

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[74] "Glassy Metals Move Into Production," *High Technology*, March/April 1982, p. 80.

[75] "Glass-Like Metals Cut Cost and Energy Use," *Machine Design*, Apr. 26, 1984.

[76] *Metal Progress*, "Trends in Powder Metallurgy Technology," January 1984, p. 58.

[77] National Materials Advisory Board, *Rapid Solidification Processing, Status and Facilities*, National Research Council, Publication NMAB-401 (Washington, DC: National Academy Press, 1982), p. 3. This unclassified document contains information which is subject to special export controls. It should not be transferred to foreign nationals in the U.S. or abroad without a validated export license. Distribution is limited to U.S. Government organizations. Other requests for the document must be referred to DARPA/TIO, 1400 Wilson Blvd., Arlington, VA 27709.

[78] NMAB-401, op. cit., p. 16.

[79] Charles River Associates, *New Metal Processing Technologies*, OTA contract report, 1983, p. 53.

[80] John K. Tien and Robert N. Jarrett, *Potential for the Development and Use of New Alloys to Reduce the Consumption of Chromium, Cobalt, and Manganese for Critical Applications*, OTA contract report, 1983, p. 9.

[81] Moore and Adam, op. cit.

[82] Parkinson, op. cit., p. 48.

RS alloys will be specifically developed to evolve as potential replacements for conventional precipitation-hardenable (PH) stainless steels, titanium alloys, and iron-based superalloys.[83]

Rapid solidification particulate technology offers great potential for the production of a new family of aluminum alloys that have properties superior to those of ingot alloys. According to NMAB, realistic property improvements likely between 1985 to 1990 include: 10-percent reduction in density, 10-percent increase in tensile strength, 15-percent increase in fatigue strength, 10-percent increase in modulus of elasticity (stiffness), and usable properties at elevated temperatures (450° F).[84] Improvements in corrosion and stress corrosion cracking resistance are also likely. These alloys are not expected to replace many strategic materials directly. Furthermore, the new aluminum alloys may contain cobalt and manganese as alloying elements. However, RS aluminum alloys will probably change the need for strategic materials because of design relationships in the applications where they are likely to be used.

Though actual in-service experience has not been accumulated, use of these new alloys is foreseen in a variety of aircraft, missile, armored vehicle, and space structure applications. Because of weight savings, significant reductions in fuel costs would be achieved.[85] Effective use of the expected improved properties will make these materials potentially competitive with various composite materials and titanium alloys for selected applications. Near-term opportunities for commercial applications, other than aircraft, are limited. Significant commercial applications have not been identified, or at least verified, with any degree of confidence.[86]

Two RS aluminum alloys have achieved production status and are being offered as extrusions, die forgings, and hand forgings. These are alloys 7090 and 7091, air-atomized 7000-series powder alloys that are modified with cobalt additions and have been developed by Alcoa.[87] The mechanical properties of 7090 and 7091 have been evaluated in several industry and government programs. In addition to good strength and fracture toughness, these alloys have excellent exfoliation and stress corrosion cracking resistance. This combination of high strength and corrosion resistance is superior to that of any existing ingot alloy. Two 7090 die forgings will be used as a main landing gear support link (an 85-pound finished forging) and an actuator component for the main landing gear doors on the Boeing 757 air transport. The components offer a 15-percent weight savings over the same parts designed with conventional alloys.[88]

The Air Force Materials Laboratory is currently working on the development of advanced second-generation alloys with improved strength and ductility properties, improved fatigue and fracture properties, increased modulus and decreased density, and improved elevated temperature properties for service at temperatures ranging from 450° to 650° F. Scale-up to production status will be initiated when adequate properties are demonstrated and is expected to be completed by 1990.[89]

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[83] Ranjan Ray, Viswanathan Panchanathan, and Saul Isserow, "Microcrystalline Iron-Base Alloys Made Using a Rapid Solidification Technology," *Metals Progress*, June 1983, p. 30.

[84] NMAB-368, op. cit. The improved properties of RS aluminum alloys derive from very small grain sizes, extended solubility or supersaturation of solute alloying elements, and very fine dispersions of dispersoid and insoluble particles.

[85] A. L. Bement and E. C. van Reuth, "Quo Vadis—RSR," *Rapid Solidification Processing; Principles and Technologies II*, R. Mehabrian, B. H. Kear, and M. Cohen (eds.) Baton Rouge, LA: Claitors Publishing Division, 1980).

[86] NMAB-368, op. cit., p. 5.

[87] 7090 Aluminum—8.0 Zinc—2.5 Magnesium—1.0 Copper—1.4 Cobalt

7091 Aluminum—6.5 Zinc—2.5 Magnesium—1.6 Copper—0.4 Cobalt.

[88] Stephen Ashley, "RS Alloys Gaining Acceptance," *American Metal Market*, 9/12/83, p. 13.

[89] NMAB-368, op. cit., p. 2.

Institutional Factors in Substitution

The potential role of direct substitutes and advanced materials in reducing U.S. strategic material needs depends not only on resolution of technical problems, but also on overcoming several institutional barriers that may impede their development. Several institutional issues are discussed below, including the general need for improved material data management, qualification and certification processes involved in substituting one metal alloy for another in critical applications, and factors affecting development of advanced ceramics and composites.

Information Availability and Substitutes

Limited access to materials properties information inhibits the use of substitute and advanced materials in many applications. The lack of a publicly accessible material property data base not only discourages direct substitution, but also frustrates the design process. In a recent study on material properties data management, the NMAB found that:

> Materials properties combined with structural analysis form the basis of modern industrial design. International competitive pressures are driving virtually all structural design in the direction of greater complexity and increased economies of production and operation. If the U.S. industrial design process is to remain competitive in this environment, engineers must have rapid access to a well organized materials properties data base.[90]

Handbooks, the traditional method of presenting material properties data, are increasingly unable to keep up with developments in a timely manner. Moreover, their methods of organizing the data are too limited. The computerized material information sources that exist are bibliographic services that search according to material properties. However, the information they provide is often cumbersome to use. According to NMAB:

> . . . the citations for a given material are frequently so numerous as to render compilation and evaluation for relevancy a very time-consuming and expensive task. Further, the interpretation of relevant data often is complicated by the lack of a standard format for presentation and the absence of sufficient information to properly characterize the material.[91]

To make the most of the wealth of materials information being generated, an on-line material properties data base with concise, thorough, and validated data would be desirable. This base would provide engineers with easy access to important information regarding substitution and design. Benefits of such a system, according to the NMAB study, would include "stimulation of innovative design, decreased design costs, and increased component reliability, and, as a result, the U.S. position in the international markets would improve."[92]

Such an on-line data base would greatly enhance the design process, especially that based on computer-aided design (CAD) and computer-aided manufacturing (CAM) systems. Also, it would disseminate a great deal of useful information to small businesses, which may not be able to support a staff of materials engineers.

There seem to be no technical barriers to the development of such a data base. A recent workshop sponsored by NBS, the Committee on Data for Science and Technology of the International Council of Scientific Unions (CODATA), Fachinformationzentrum, and Oak Ridge National Laboratory (ORNL) found that the major problem is selecting the best organization to lead the effort, raise the necessary funds, and coordinate the required technical expertise.[93]

Finally, it should be mentioned that the dearth of easily accessible properties data is a particularly acute problem for advanced materials, such as composites and ceramics. The great potential of these new materials lies in the innovative structural designs that they make possible. However, in order to examine a wide array of structural configurations and to use most effectively the special capabilities of the materials, the design process must be computer assisted. An on-line material properties data base would be an integral part of such a design system. However, not only are machine-readable data not widely available, but information in any form is difficult to come by. Much of the development work on advanced materials is done by end users (as opposed to suppliers) who have no interest in promoting the material outside their company or industry. Therefore, properties data are often unavailable for use in other applications.

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[90] National Materials Advisory Board, *Materials Properties Data Management—Approaches to a Critical National Need*, NMAB-405 (Washington, DC: National Academy Press, 1983).

[91] Ibid., p. 3.

[92] Ibid., p. 33.

[93] Ibid., p. 3 and 102.

Qualification and Certification of Alloy Substitutes

Currently, many promising alloy substitutes are under development that have potential to reduce strategic materials requirements. Actual use of these materials by industry is problematic. Many of these substitute materials will not be tested and developed to the point where they can be considered on-the-shelf technologies that will be immediately available in a supply disruption.

A major reason for this is that industry is not likely to commit resources to qualify and certify new materials that it does not have immediate plans to use. Qualification and certification is needed in many critical applications—those in which substitution could be most important to reduced import vulnerability—yet few substitutes will be taken through this process because of the time and cost involved. This barrier appears greatest when there is no evident economic driving force to entice industry to engage in the process. Such is the case for many strategic materials substitutions—government, not industry, is the party with the most concern for making sure that the new alloy gains customer acceptance. In addition, owing to their critical applications, the certification process for strategic materials substitutes is more demanding of time and data, which translates into cost.

Two examples of alloy certification processes—one for stainless steel, the other for superalloys—are discussed below.

Stainless Steel

As the earlier section on substitution prospects suggests, several promising low- or no-chromium alloys could serve as alternatives to currently used stainless steels and nonstainless alloy steels. Actual use of technically promising, lower chromium substitutes will depend on acceptance of these new materials by producers and end users. For many consumer and decorative steel applications, substitution of a new material is a comparatively simple matter—often entailing a decision to switch by a manufacturer. For critical applications, however, extensive testing and certification is essential before widespread use.

In contrast to superalloys, in which company-oriented qualification of materials predominates, certification of new stainless steels and alloy steels is usually undertaken through committees of professional societies or trade associations, often through voluntary donation of time and facilities by producers and end users. Such activities may take 10 years or more if the immediate need is small, and can slow the process of user acceptance of replacement materials.

An instructive example of the steps entailed in qualifying a new material in a critical application is provided by the ongoing effort by DOE to qualify a new alloy as a boiler and pressure vessel material. The initial steps toward development of the alloy began in 1974, when a task force set up by DOE (then called the Energy Research and Development Administration) recommended a program to develop reference structural alloys for use in the liquid metal fast breeder reactor.[94] The alloy development process was sponsored through two offices in the DOE under an Oak Ridge National Laboratory contract with Union Carbide Corp., and in conjunction with Combustion Engineering, Inc. After studying several alternative alloys, a modified 9Cr-1Mo alloy was selected for further development. Data development for qualification began in 1979, but the alloy has yet to be approved for widespread commercial use. The purpose of the effort was not to conserve chromium, but rather to provide a uniform construction material for boilers and pressure vessels. Figure 7-6 shows the development "ladder" for this alloy.

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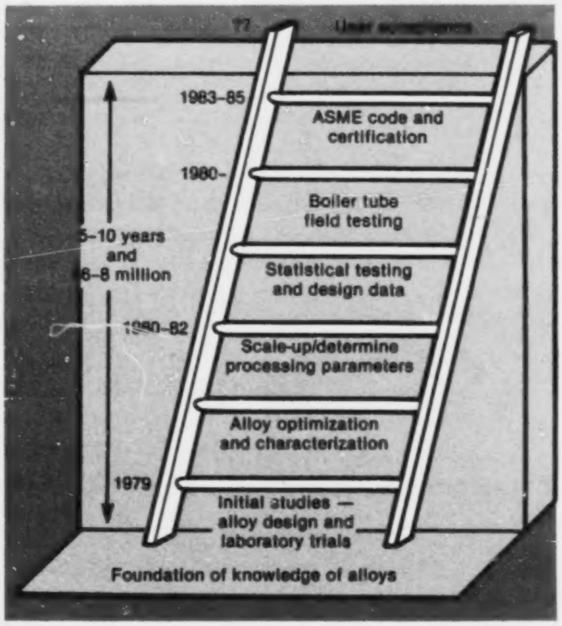
[94] The history of the 9-1 alloy is discussed in P. Patriarca, E. E. Hoffman, and G. W. Cunningham, "Historical Background" in P. Patriarca, compiler, *ORNL Technology Transfer for Meeting A New Chromium-Molybdenum Steel for Commercial Applications* (Oak Ridge, TN: Oak Ridge National Laboratory, Apr. 7, 1982).

Once initial laboratory work had been undertaken, the need to demonstrate reliable transfer of properties through scale-up and field testing arose. Under arrangements with several alloy producers, commercial heats (ranging from 0.5 to 15 tons) were made using several commonly used processing practices (e.g., AOD and vacuum induction melting). The commercial heats were then formed into plates, bars, tubes, and pipes, using a variety of fabrication processes. To provide additional test data, modified 9Cr-1Mo alloy replacements for 18-percent stainless steel tubes have been put in service in six conventional powerplants located in the United States, Canada, and Great Britain, as shown in table 7-17.

Figure 7-6.—Development of Modified 9Cr-1Mo Steel for Fossil Fuel and Nuclear Power Applications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User acceptance
1983-85
ASME code and certification
1980-
Boiler tube field testing
5-10 years and $6-8 million
Statistical testing and design data
1980-82
Scale-up/determine processing parameters
Alloy optimization and characterization
1979
Initial studies — alloy design and laboratory trials
Foundation of knowledge of alloys

SOURCE: John K. Tien and Robert N. Jarrett, *Potential for the Development and Use of New Alloys to Reduce the Consumption of Chromium, Cobalt, and Manganese for Critical Applications*, OTA contract report, September 1983.

Widespread, nonexperimental use of this substitute in powerplant applications is dependent first on approval of its specifications by the American Society for Testing of Materials (ASTM), followed by its inclusion in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.

In May 1981, an application was made to ASTM to approve specification of the modified 9Cr-1Mo alloy for use in plate and tube products, followed a year later by a similar request for forgings, pipings, and fittings. The specifications are currently working their way through the ASTM approval process, as shown in table 7-18. A data package for inclusion of the material in the ASME Boiler and Pressure Vessel Code pertaining to nonnuclear applications was provided in June 1982. Additional data will have to be collected before the substitute material can be considered for possible use in nuclear powerplants.

By early 1984, the alloy had been approved for certain limited uses in conventional (nonnuclear) powerplants. Additional applications for the alloy can be expected to be approved sometime in 1985—9 years after initial design of the alloy. Estimated costs for the post-laboratory alloy development through the end of 1983 are $5 million by the government (an estimated $2 million has been donated in services by industry).[95]

Superalloys

As suggested previously, several current and prospective materials and technologies could be used to reduce cobalt and, to a lesser extent, chromium use in the hot sections of gas turbine engines. Some, perhaps most, of these may have the technical potential to reduce stra-

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[95] Information provided by V. Sikka, Oak Ridge National Laboratory.

Table 7-17.—Current Status of Testing of Modified 8Cr-1Mo Steel Tubes in U.S. and Foreign Steam Powerplants

Utility	Plant	Tube location	Operating temperature (°C)	Tubes being replaced	Number of tubes	Date installed	Status
Tennessee Valley Authority	Kingston Steam Plant, Unit 3	Superheater	593	Type 321	8	May 1980	Operating
American Electric Power	Tanners Creek Unit 3	Secondary superheater	593	Type 304	10	April 1981	Operating
Detroit Edison	St. Clair Unit 2	Reheater	538	Type 347	2	February 1981	Operating
Central Electric Generating Board (U.K)	Agecroft Power Station	Superheater	590-620	2¼ Cr-1 Mo	6	April 1982	Operating
Ontario Hydro (Canada)	Lambton TGS	Reheater	538	Type 304H	9	May 1983	Operating
		Reheater	538	Standard 9 Cr-1 Mo	9		
Ontario Hydro (Canada)	Nanticoke TGS	Secondary superheater	538	2¼ Cr-1 Mo	11	April 1984	Planned

SOURCE: V. K. Sikka and P. Patriarca, *Data Package for Modified 9Cr-1Mo Alloy* (Oak Ridge, TN: Oak Ridge National Laboratory, December 1983), p. 28.

Table 7-18.—Status of Specifications for Modified 9Cr-1Mo Alloy

Specification number	Description	Status as of December 1983
A-213 T91	Seamless ferritic and austenitic alloy-steel, boiler, superheater, and heat-exchanger tubes	Approved and available as separate
A-387 GR91	Pressure vessel, plates, alloy steel, chromium-molybdenum	Approved by Main Committee and awaiting Society Ballot
A-182 F91	Forged or rolled alloy-steel pipe flanges, forged fittings, and valves and parts for high-temperature service	Approved by Main Committee and awaiting Society Ballot
A-234 WP91	Piping fittings of wrought carbon steel and alloy for moderate and elevated temperatures	Approved by Main Committee and awaiting Society Ballot
A-335 P91	Seamless ferritic alloy steel pipe for high-temperature service	Approved by Main Committee and awaiting Society Ballot
A-336 F91	Steel forgings, alloy, for pressure and high-temperature parts	To be submitted for AI.06 Subcommittee approval
A-199 T91	Seamless cold-drawn intermediate alloy-steel heat-exchanger and condenser tubes	To be submitted for AI.10 Subcommittee approval
A-369 FP91	Carbon and ferritic alloy-steel forged and bored pipe for high-temperature service	To be submitted for AI.10 Subcommittee approval

SOURCE: V. K. Sikka and P. Patriarca, *Data Package for Modified 9Cr-1Mo Alloy* (Oak Ridge, TN: Oak Ridge National Laboratory, December 1983), p. 5.

tegic materials without impairing the advances in performance so critical to the military. However, aside from those that are already fully developed, most of these potential substitutes still face massive R&D costs, and, if they prove viable, large scale-up and qualification costs. Given industry's little incentive to assume these costs itself, unless clear performance and cost benefits would also accrue, most of the resources available for qualifying new superalloys are dedicated to prospective materials to be used in the next generation of jet engines.

Successful commercialization of a new superalloy for the hot section of a gas turbine engine can take two decades, beginning with the researcher's idea, through laboratory proof-of-concept, to engine testing and eventual commercial application. Many research ideas never reach the laboratory stage, and of those that do, only some show technical promise.

Even when technical problems can be overcome, institutional barriers can add appreciably to development time or can indefinitely delay work on the project. Given the protracted time period involved, what may have been initially seen as a clear need for a new material may not be relevant a decade later. Many superalloy development efforts are cost-shared between government and industry, which adds to the risk that R&D priorities will change during the course of the project. Coordination of research may also be difficult. By the time commercialization of a superalloy is successfully reached, several different government agen-

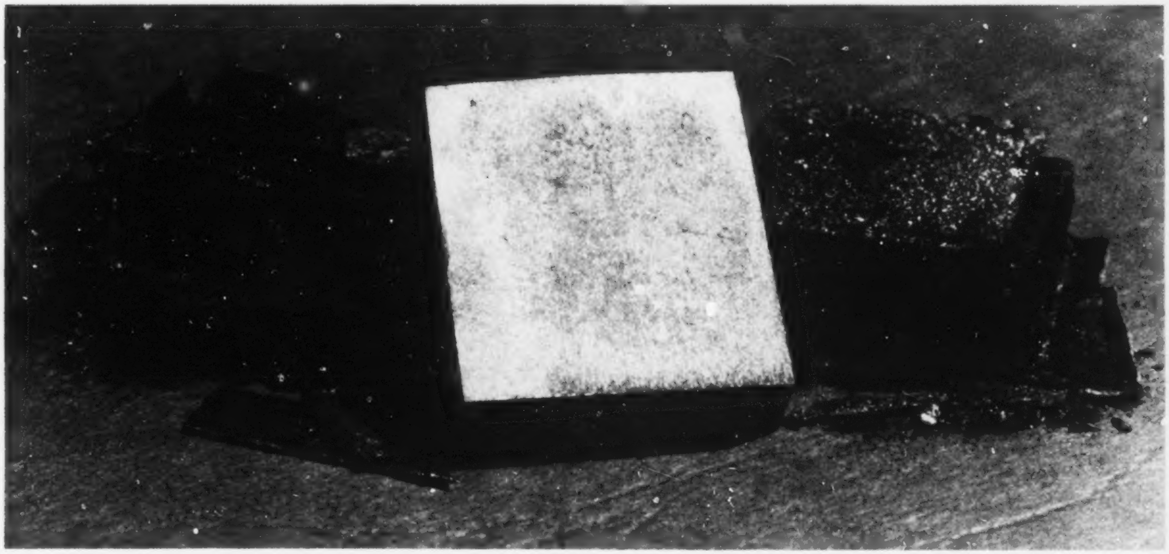


Photo credit: U.S. Department of the Interior, Bureau of Mines

Aluminum and silicon can reduce the need for chromium in stainless steels for high-temperature applications. A 5-percent aluminum addition to a Bureau of Mines 17Cr-8Ni research alloy (center) enormously improves oxidation resistance after 380 hours at 1,000° C compared to type 304 (18Cr-8Ni) and type 316 (18Cr-12Ni) stainless steels. The research alloy is under investigation as a possible high-performance alternative to the 25 percent Cr-20 percent Ni stainless steels

cies, universities, and companies may become involved—each with its own specific objectives, personnel, and priorities.

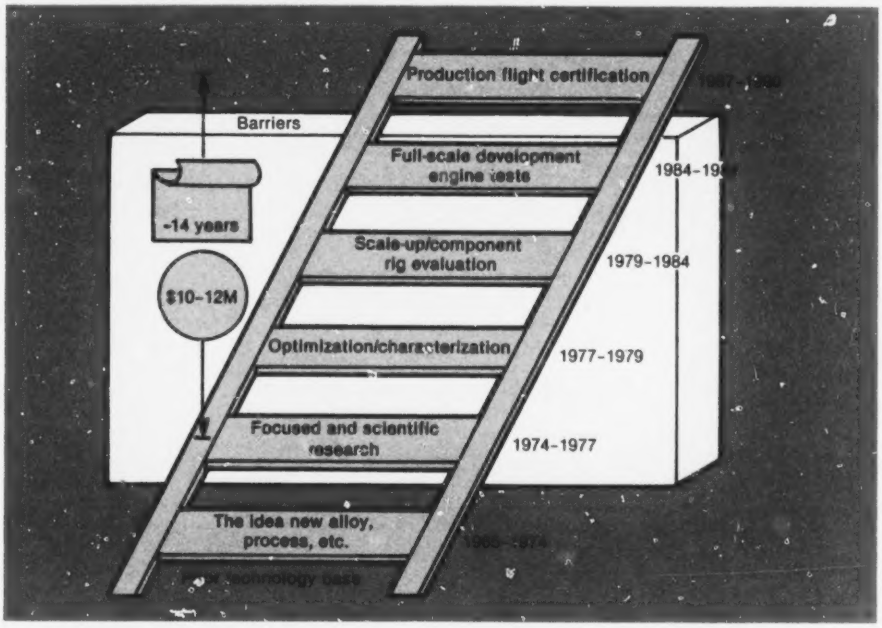
Typically, laboratory findings must be verified in large-scale industrial heats. It is only at this stage that the technical validity and manufacturing practicality of the process can be known with assurance, and it is only at this stage that the expensive and time-consuming process of engine qualification can begin. Designer and user acceptance of the new material will occur only when there is confidence about its reliability and performance at acceptable costs.

Figure 7-7 shows key steps that must be overcome in the successful commercialization of a new superalloy, using Inconel MA 6000 as an example. Inconel MA 6000 contains no cobalt, but its initial development had nothing to do with conservation of strategic materials. Rather, the key objective was to develop a turbine blade material able to operate at a higher temperature than other superalloys, while avoiding the performance penalties associated with the need for cooling air.

The origins of Inconel MA 6000 date back to 1968, with the invention by a researcher at the International Nickel Co. of a mechanical alloying process for producing oxide dispersion strengthened superalloys. In 1974, NASA entered the picture by providing Inco with support to design an alloy composition that became MA 6000. In time, university researchers and several manufacturers of jet engines became participants in the project as it advanced through scale-up to its present status—preparation for engine testing. If successful, it will probably be another 5 years before MA 6000 is actually used for turbine blades and vanes in human-rated jet engines. Using 1974 as a starting date, 15 or more years—and an estimated $10 million to $12 million—will have been consumed in the development of this one cobalt-free superalloy.

Development costs associated with an entirely new superalloy may be greater than for

Figure 7-7.—Technology Transfer Ladder for ODS MA 6000


Production flight certification
1987-1990
Barriers
Full-scale development engine tests
1984-19
~14 years
Scale-up/component rig evaluation
1979-1984
$10-12M
Optimization/characterization
1977-1979
Focused and scientific research
1974-1977
The idea new alloy, process, etc.
1965-1974
Prior technology base

SOURCE: Joseph R. Stephens and John K. Tien, *Considerations of Technology Transfer Barriers in the Modification of Strategic Superalloys for Aircraft Turbine Engines*, NASA Technical Memorandum 83395 (Springfield, VA: National Technical Information Service, 1983).

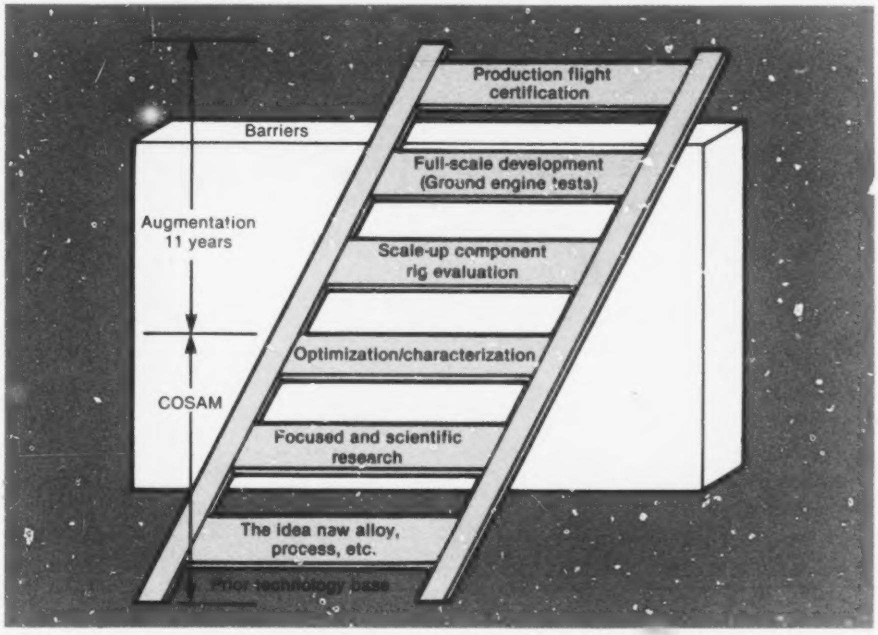
a superalloy with a modified composition. For example, the low- or no-cobalt COSAM alternatives are intended as substitutes for existing superalloys. If the alternative materials were commercially used, it is probable that only minor adjustments in manufacturing and fabrication processes would be needed. In this regard, NASA's proposed fiscal year 1985 budget earmarks $50,000 for preparing several test heats of one of its four low-cobalt, alternative superalloys. Figure 7-8 shows steps taken to date and additional development required for the COSAM superalloys.

Institutional barriers to continued development of the materials are formidable, even if their technical promise is favorable. In the case of the low-cobalt COSAM alternative superalloys, post COSAM augmentation efforts could require 6 to 7 years and $6 million to $9 million, assuming real-time testing requirements and typical scale-up activities for each modified alloy. Since the COSAM alternative superalloys would substitute for already used, widely accepted, higher cobalt superalloys, no single company is likely to be committed to assuming such a development effort simply for the purpose of contingency planning for a hypothetical future cobalt shortage.

Institutional Barriers and Advanced Materials

Advanced materials face a number of institutional barriers before being adopted on a major scale. As comparatively new technologies and new industries, they need the support of more complete and reliable data than is currently available and of innovative design which uses the materials to their best advantage. In the end, final acceptance of advanced materials by engineers, designers, and consumers will come only from experience in use. The Federal Government's efforts focused on these new materials can assist in this adoption process and promote the growth of new industries.

Figure 7-8.—Technology Transfer Ladder for COSAM Strategic Material Substitution


Production flight certification
Barriers
Full-scale development (Ground engine tests)
Augmentation 11 years
Scale-up component rig evaluation
Optimization/characterization
COSAM
Focused and scientific research
The idea naw alloy, process, etc.
Prior technology base

SOURCE: Joseph R. Stephens and John K. Tien, *Considerations of Technology Transfer Barriers in the Modification of Strategic Superalloys for Aircraft Turbine Engines*, NASA Technical Memorandum 83395 (Springfield, VA: National Technical Information Service, 1983).

Ceramics Data Base Requirements, Standards, and Qualification Processes

The properties of ceramic components and the materials from which they are made—and thus their usefulness for any particular application—can vary depending on their chemical formula and the methods by which they are produced. One of today's largest single institutional constraints to expanded structural usage of ceramics is the poor quality and limited availability of information on these variable material properties. The technology needs not only the application of standardized test procedures (specific to materials and processing and the effect of different temperature and chemical environments over time) and a systematic collection of available information but also research efforts devoted to producing the information.[96]

Designer Preference and Education

Product design engineers select materials on the basis of past experience and available data. Few structural design engineers have experience with ceramics (less so with composites). As stated above, reliable data about material properties are scarce, and in general, formal codes and specifications do not yet exist. Such data bases normally serve as guides for engineers working with unfamiliar materials.

In general, the formal education received by engineering students is deficient both in knowledge obtained about advanced materials and in how to incorporate that knowledge into design work. For instance, materials courses are not generally required of mechanical engineering students, and if they are, the emphasis is on metals. Educational institutions are reluctant to adjust long-established curricula to eliminate such deficiencies and may often be constrained by budgets from doing so. In a broader context, the base of 10 to 15 universities in the United States with programs in ceramics may be insufficient to meet the future research needs of a rapidly expanding industry.

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[96] The National Bureau of Standards recently announced the establishment of a Ceramic Powder Characterization Laboratory (*NBS Update*, June 11, 1984). The laboratory will help manufacturers by providing them with information on powder characteristics.

Industry in Transition

The advanced ceramics industry is being created out of discrete parts of other industries. The mature traditional ceramics industry, conservative because of a history of stable and profitable years, is only now examining new possibilities. This change in perspective may be a result of recent depressed conventional markets (linked to the steel industry) and talk of future competition from abroad. Most of the innovations in the industry, however, appear to come from end users rather than from the producers. Much of the research conducted by end users naturally leads them into becoming materials processors in order to maintain the necessary tight control over this critical step. Other segments of this emerging industry are the expansion into advanced ceramics by conglomerates and conventional materials firms that sense future market changes.

This merging process means that there is no focal point, no industrial champion for advanced ceramics. As yet, no industrial association or organization is charged with research, development, or product data specification. The established professional association—the American Ceramics Society—provides a forum for the exchange of technical information. It does not, however, have a technical section dealing with advanced ceramics as a separate issue. Recently, it has begun to collect data on industry production of advanced ceramics and form a standardized data bank. With little information yet available about the organization of the industry and its participants, government data collection centers, such as those of the Department of Commerce,[97] EPA, and OSHA, do not yet aggregate advanced ceramics data separate from that of the traditional ceramics industry.

Government Research

Currently, several agencies are involved in many aspects of advanced ceramics research: primarily, DOE, Department of Defense, NASA, and NSF. Those interested in the advancement of the technology express concern over the uncertainty from year to year over adequacy of funding, the direction of funding, and possible lack of coordination which may lead to duplication of effort.

The bulk of the research effort is focused on the high potential (in terms of market size, energy efficiencies, and strategic materials substitution) heat engine applications. While this may be appropriate from an applications point of view, questions remain as to whether concentration on major development projects is the best way to advance the science of advanced ceramics and whether this approach will contribute to the building of a firm, broad base of technical knowledge for the support of a competitive domestic industry. Supporters of the concept argue that the technological base is broadened by focusing on the development of a major application, since success requires an iterative process in which researchers must continually return to basic science in order to solve problems encountered in the development phase. Others worry that, by pushing the development phase at the expense of basic research, application failures which occur will result in generating negative impressions of the ultimate capabilities of the technology.

The current contractors on the ceramic heat engine projects have plans to commercialize the technology eventually, but a technology gap will exist after the proof-of-concept stage is reached by government R&D efforts. The skills developed in designing the ceramic components of experimental engines will be transferable to engines designed with the consumer in mind. But industry will have to be firmly convinced of the technology's viability to be willing and able to take on expensive and lengthy development costs before ceramic heat engines are ready for the marketplace.

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[97] Information is beginning to emerge, however. See, for instance, U.S. Department of Commerce, *A Competitive Assessment of the U.S. Advanced Ceramics Industry*, March 1984.

Until recently, there was no Federal office with a specific mission to promote, coordinate, and focus the government's R&D efforts in advanced ceramics. (As is discussed in chapter 8, the National Critical Materials Act of 1984 establishes a council in the Executive Office of the President that is to formulate a Federal program plan for advanced materials.) It is currently difficult to obtain a comprehensive overview of the R&D efforts of the various agencies and to determine whether there is any overlap of effort. Table 7-19 provides a breakdown by agency of estimated Federal Government R&D for structural ceramics technology. This reflects internal shifts of program emphasis and is a result of a growing awareness in many sectors of the important role that advanced ceramic technology could play in future U.S. economy.[98]

DOE has initiated some steps to cope with the lack of available information. Its Oak Ridge National Laboratory (ORNL), in its Ceramic Technology for Advanced Heat Engines Program Plan,[99] provides a breakdown of the funds committed by various agencies for R&D in advanced ceramics considered applicable to heat engine technology. The Advanced Materials Development Program at DOE is developing a computer-based data system which, when completed, will provide continuing—and systematically collected—information on the R&D efforts in structural ceramics of Federal Government agencies.

Even with these statistics available, overlap of effort is difficult to assess. The difficulty lies, in part, in the large and growing number of advanced ceramic materials, each designed with specific properties for specific applications (similar to metallic alloys). While the knowledge gained from success in one application, if transferred, can advance the use of similar ceramic materials in another application, a material designed for a specific application cannot necessarily serve "as is" elsewhere.

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[98] Robert B. Schulz, Program Manager, Advanced Materials Development Program, Department of Energy, personal communication, Oct. 4, 1984.

[99] Oak Ridge National Laboratory, *Ceramic Technology for Advanced Heat Engines Program Plan*, ORNL/TM-8896, June 1984.

Table 7-19.—Structural Ceramic Technology Federal Government Funded R&D (in millions of dollars)

	Fiscal year 1982	Fiscal year 1983	Fiscal year 1984	Fiscal year 1985
Department of Energy:				
• Conservation and renewable energy:				
— Heat engine propulsion	$ 9.3	$14.6	$15.5	$13.6
— Industrial programs	1.5	1.0	2.3	2.7
— Energy utilization research	0.3	0.5	0.6	2.0
• Fossil energy:				
— Advanced research and technology development	1.2	1.0	1.0	1.0
— Advanced energy conversion systems	1.9			
• Energy research:				
— Basic energy science	2.0	3.0[a]	3.0	3.0
NASA:				
• Lewis Research Center[b]	1.8	3.0	3.5	4.6
NSF	2.7	2.9	3.3	3.6
Department of Defense:				
• Defense ARPA	2.0	7.7	9.5	7.7
• U.S. Air Force	1.7	3.0	3.4	4.7
• U.S. Army	1.3	4.7[c]	6.0[c]	2.5[c]
• U.S. Navy	1.0	1.2	1.3	1.4
Total	$26.7	$42.6	$49.4	$46.8

[a] Reflects increase in portion of budget applied to structural ceramics.
[b] Includes salaries for manpower.
[c] TACOM included.

SOURCE: U.S. Department of Energy, Advanced Materials Program, October 1984.

Despite the lack of official oversight, coordination among agencies has apparently improved in recent years. The ORNL program plan on ceramic heat engine technology was developed to identify technology base needs; develop a multi-year technical and resource agenda; and coordinate activities with other industry, government, and university programs. NASA holds regular and frequent meetings with DOE that now include DARPA and the Air Force. Each fall, an interagency meeting is held for all the participants from government, industry, and academia working on ceramics in heat engines.

NASA's Lewis Research Center has also developed a new comprehensive ceramics program proposal but funding was not included in the fiscal year 1985 budget. The program's goal, while focused on the aircraft engine as the application, was to broaden the ceramics technology base in general.

The National Science Foundation, under its industry and university cooperation program, has funded the Center for Ceramic Research at Rutgers University. This center has been granted public funding for 5 years with the intent that it will be able to generate sustaining private funding of its research efforts within that period. Research areas in which the Center is involved include, among other things, powder processing technologies and improvement of materials properties.

Qualification, Certification, and Standardization of Composites[109]

Composites are engineered materials, and as such are very sensitive to a multitude of structural and processing factors. This characteristic is very beneficial, because it gives designers great control over the properties of composites, allowing the tailoring of these materials to individual applications. However, with the greater design flexibility also comes the need for strict materials and processing tolerances during production runs. Addressing the concerns arising from the sensitivity of composites to each manufacturing step, the composites industry has adopted elaborate certification and qualification schemes. These procedures are needed to ensure the quality and uniformity of the various materials, through the many times they change hands, used in the production of composites.

Qualification and certification is more complex for composites than for traditional materials for several reasons.

The composites industry is very fragmented—there is very little vertical integration. There are many processing steps entailed in the production of composites, and rarely, if ever, does one company engage in all these segments of the business. Most composites companies are specialized, each concentrating on a segment of the industry.

While this may not increase the amount of testing needed to ensure product quality and uniformity, it causes confusion with regard to testing needs and data interpretation.

Composites are fundamentally different in their structure and behavior than traditional materials. The well established testing and characterization techniques used for traditional materials are not suited for composites. Appropriate composites testing techniques have been developed, but on an ad hoc basis with little industrywide agreement.

There is no uniform procedure for certifying and qualifying composite materials and structures; every product is handled differently, on a company-by-company basis.

The composites industry has no industry association to pursue the interests of the composites industry as a whole. There is no organization through which the industry can work on qualification, certification, and standardization problems common to many of the involved companies.

Developing the data package necessary for qualification of composite materials and structures is very time-consuming and expensive (especially considering the small quantities of materials often associated with composite orders). The battery of tests required to qualify a material may cost $20,000 to $200,000 or more, depending on the scope of testing. While these costs are borne by the composites user for the initial supplier's material, alternate suppliers may be required to assume part or all of their qualification costs. The new suppliers may be required to perform costly full-scale tests if bench-scale evaluation suggests significant differences between their material and the primary material. Qualification of a new supplier for an existing material may require 3 to 6 months for most structural applications. Whenever any change is made in the composites used in rocket nozzles, full-scale testing—taking up to a year—is required. This costly testing limits the number of suppliers for any given application.

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[109] This section draws heavily on Stanley L. Channon, "Industrial Base and Qualification of Composite Materials and Structures (An Executive Overview)" (Alexandria, VA: Institute for Defense Analysis, May 1984). Presented as a working paper for a Department of Defense-sponsored colloquium/workshop on *Composite Materials: Standardization, Qualification, Certification*, Washington, DC, May 1984.

In addition to being costly, the complexity of the qualification process may discourage innovation. Once a composite has been qualified for a particular use, changes in the material or its production are usually disallowed for that application. This, along with designers' preference for proven materials, tends to restrict the number of available qualified materials.

There is also a need for standardization of material specifications and test methods for composites. Standards are currently generated by a variety of government and industry groups, but it is customary to rely on specifications from fiber and resin suppliers. The government specifications are rarely used because they are too broad or out of date. Industry groups such as the American Society for Testing and Materials (ASTM), the American National Standards Institute (ANSI), the Society of Automotive Engineers (SAE) and others generate composites standards, but the process is slow and often includes compromises accepted in order to broaden the applicability of the specifications. ASTM test methods find frequent use in industry, but many companies develop their own test methods because of preferences in testing equipment and procedures.

Regarding the need for standardization of composite materials, a recent industry survey concluded:

> Although the majority of industry and government personnel would prefer to see standards adopted for the composites industry, it is recognized that this will not be acomplished easily. A major resistance to standardization emanates from the suppliers of materials who fear that the identity of their materials would be lost. . . Some opponents to standardization feel that this would retard technological innovation in the industry whereas proponents feel that the industry will advance more rapidly if standards are adopted. Some feel that the timing is inappropriate for standardization because the industry is still in a dynamic state.[101]

Composites technology also faces other institutional barriers similar to those for ceramics, although it is probably far ahead in most aspects. The technology has found its major application in the aircraft and automotive industries and has been supported and pushed by those industries and by the government. The extensive government research in composites has been centered primarily in the Department of Defense. The interest in composites for use in military aircraft, and the accompanying lack of public information, however, has been blamed for slowing technology transfer between the government, academia, and industry.

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[101] Ibid., p. 22.

CHAPTER 8

Policy Alternatives for Strategic Materials

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CHAPTER 8

Policy Alternatives for Strategic Materials

The central premise that underlies concern about strategic materials can be stated as follows: the United States must import a number of materials that are essential to the national defense and to domestic industry. For a number of these materials, the bulk of the supply comes from countries or regions that are either politically unstable or ideologically hostile to the United States. As a result, the United States may face disruptions in the supply of these materials, disruptions that could be damaging to the national defense or industrial strength of the country.

The National Defense Stockpile and the priority allocation system provided under the Defense Production Act address the problem of maintaining an adequate supply of materials for national defense. These policies and procedures, however, are not meant to protect the U.S. industrial economy from disruptions in the supply of strategic materials except in times of war or national emergency.

The technical approaches that are the subject of this report can help reduce the vulnerability of the United States to disruptions in the supply of strategic materials. The approaches can be grouped into three categories: mineral production and processing, conservation and recycling, and substitution. Policy options for the implementation of these approaches, including the formulation of coordinated Federal strategies for strategic materials, are the subject of this chapter.

Two general observations apply to the discussion in this chapter. First, most of these technical approaches are long-term in nature. Some of the alternatives, such as the development of substitute materials for the most demanding applications, may require 10 years or more to be brought to fruition. Second, private industry, not the Federal Government, is the primary producer, importer, and consumer of strategic materials. Therefore, it is private industry that will make most decisions about the location of new mineral development, about the use of conservation and recycling technologies, and about the development and use of substitute materials.

The Federal Government can influence private decisions through such actions as support of research and development or use of tax and other economic tools to influence investments. The degree of government involvement considered appropriate or desirable depends on the policymaker's assessment of the likelihood and effect of supply disruptions, on his or her philosophy of the relationship of government and industry, and on the economic and technical resources available for this issue in the wide range of national affairs.

Potential Contribution of Alternatives to Specific Material Supplies

Prospects for reducing vulnerability must be assessed on a material-by-material basis. The potential contribution of each alternative differs for each strategic metal under examination; however, taken in sum, these alternatives can contribute significantly to net reduction of U.S. vulnerability to disruptions of supplies of strategic materials.

Table 8-1 illustrates how each technical alternative relates to the first-tier strategic materials (chromium, cobalt, manganese, and platinum group metals) that are addressed in detail in this study. These alternatives are summarized briefly below. Detailed discussion of the technical alternatives to import vulnerability is provided in chapter 5 (production and processing),

Table 8-1.—Technical Prospects for Reducing U.S. Import Vulnerability for Chromium, Cobalt, Manganese, and the Platinum Group Metals

	Chromium (Cr)	Cobalt (Co)	Manganese (Mn)	Platinum group (PGM)
U.S. apparent consumption (1982)[a]	319,000 short tons	5,592 short tons (11,184,000 lbs)	672,000 short tons	61 short tons (1,787,000 troy ounces)
U.S. import dependence (1982)[a]	85%	92%	99%	80%
Recycling in 1982 (purchased scrap)[b]	12%	8%	Not estimated[b]	19% (excludes toll refined)
Domestic production in 1982[a]	0%	0%	About 2% of apparent consumption	0.4% of apparent consumption
Price in 1982[a]	Turkish chromite: $100/short ton ($110/metric) South African: $47/short ton ($52/metric).	Cathode 99% Co: $12.90/pound	About $1.58-$1.68 per long ton unit (22.4 pounds) of 46 to 48% of Mn metallurgical ore.	Dealer Price: platinum—$327/troy oz.; palladium—$67/troy oz.
Value of imports into the United States in 1982[c] (including gross weight)	$120 million	$143 million	$197 million	$554 million
Import sources (1979-1982)[a] (Bold-faced countries are primary producers)	Chromite: **South Africa** (48%); **U.S.S.R.** (17%); **Philippines** (13%); Other (22%). Ferrochromium: **South Africa** (44%); Yugoslavia (9%); **Zimbabwe** (9%); Other (38%).	**Zaire** (37%); **Zambia** (13%); **Canada** (8%); Belgium-Luxembourg (8%); Japan (7%); Norway (7%); Other (13%).	Ore: **South Africa** (33%); **Gabon** (26%); **Australia** (20%); **Brazil** (12%); Other (9%). Ferromanganese: **South Africa** (43%); France (26%); Other (31%).	**South Africa** (56%); **U.S.S.R.** (16%); U.K. (11%); Other (17%).
Location of major world reserves[d]	South Africa and Zimbabwe (92%); the remaining 8%, distributed among more than 10 countries, represents reserves in excess of 100 million short tons of chromite. Chromite typically ranges from 22 to 38% chromium content.	Zaire (50%); Zambia (13%); Cuba (7%); U.S.S.R. (5%); the remaining 25% of world reserves (2 million short tons) is distributed among 12 countries.	South Africa (40%); U.S.S.R. (37%); remaining 23% (distributed among 8 countries) represents reserves in excess of 200 million short tons.	South Africa (79%); U.S.S.R. (19%); remaining 2% (20 million troy ounces) is in Canada, the U.S., and Columbia.
Prospects for increased substitution	Very good for noncritical applications; for critical applications, extensive applied R&D will be needed. Basic research breakthroughs may be needed to develop substitutes in the most critical applications.	Good for many applications; additional R&D needed for critical applications such as superalloys. Qualification requirements may limit practical use of these substitutes.	Poor—substitutes for Mn in steelmaking (which accounts for 90% of consumption) are not promising.	Alternatives to PGM exist in many applications; in critical applications, prospects for direct substitution are poor in the near and medium term.
Potential for displacement by advanced materials	Fiber-reinforced plastics and some other composite materials may compete with stainless steels in some critical applications over time.	Reasonable prospects for incremental phase-in of advanced materials in near and medium term; long-term prospects (2010 and beyond) may be great in heat engine applications.	Limited: various composites may compete with steel in specialized applications.	Breakthrough in basic research is probably needed for other materials to replace PGM as a catalyst.
Potential for increased recycling	Good—major obstacles are economic. Reduced downgrading, improved obsolete scrap recovery, and recovery of Cr values from steelmaking wastes appear to be the major opportunities, although data is out-of-date. Scrapped catalytic converter shells could become source of Cr; recovery of Cr from steelmaking wastes also may add to supplies.	Good—economic factors are primary impediments to recycling, although advanced technologies may have to be developed to maximize recovery of superalloy scrap. Obsolete superalloy scrap, spent catalysts, and other postconsumer uses will be a growing potential source of cobalt. For 1980, an estimated 2,350 short tons (4.7 million lbs) of Co was not recycled or was downgraded.	Poor—unless technical advances make Mn recovery from slag economical.	Excellent—recycling of PGM from automotive catalysts could provide 400,000 to 500,000 troy ounces of PGM annually in the mid-1990s. Obsolete electronic scrap could also be a major recycling source if high costs of disassembly are overcome.

Table 8-1.—Technical Prospects for Reducing U.S. Import Vulnerability for Chromium, Cobalt, Manganese, and the Platinum Group Metals (Continued)

	Chromium (Cr)	Cobalt (Co)	Manganese (Mn)	Platinum group (PGM)
Potential for more efficient use through design, processing, and manufacturing technologies	Incremental gains; a major breakthrough akin to the AOD process, which reduced chromium losses in stainless steel production is not foreseen.	Very good—in superalloy production and parts fabrication; however, more efficient manufacturing will reduce scrap materials most preferred for recycling.	Good—manganese required per ton of steel could be reduced significantly by the year 2000 (from the current level of 36 lbs/ton to 25 lbs/ton).	Uncertain—will depend on basic research in catalyst chemistry.
Prospects for production and processing:				
Potential for significant domestic production	Very poor—known deposits are low in quality and probably will not be exploitable except in a national emergency; however possibility of a new discovery of a promising deposit cannot be ruled out entirely. In addition, limited quantities of chromite may be produced as a byproduct if nickel-cobalt laterites are developed.	Poor—without subsidy or major price rise. Good with subsidy. Maximum simultaneous development from existing mine sites could provide 10 million pounds (5,000 short tons) of cobalt annually for a 10- to 15-year period. Production economics varies by mine site. Mine owners have cited prices ranging from $16 to $25 per pound as needed where cobalt is the primary mine product. At other sites, prices of nickel and copper need to be considered in determining whether coproduction would be profitable.	Very poor—known deposits very low in quality. Possible discovery of a promising deposit cannot be ruled out entirely.	Fair to good—initial plans to develop one domestic site anticipate palladium and platinum production equivalent to 9 % of total U.S. PGM consumption in 1982. A decision on the project is expected in 1985. Much higher production levels may be achievable if other sites are developed.
Potential for supply diversification abroad	Poor to fair—probably would require U.S. development assistance or incentives to promote production in Turkey, the Philippines, and several other countries.	Good prospects—but viability depends on copper and nickel markets because cobalt is a byproduct from mining of these materials. Improved technologies for laterite processing in the U.S. may be transferable overseas.	Good—several alternative suppliers exist, including Mexico, Australia, Brazil, and Gabon.	Poor—unless major new discoveries are made (U.S. has most promising unexploited deposit).
Potential to retain domestic processing capacity	Loss of processing capacity is expected to continue in near term with stabilization of domestic industry at a reduced level in long term to meet specialty steel industry needs.	Good—processing capacity is expanding due to recycling efforts	Loss of processing capacity is expected to continue in near term with stabilization of industry at a reduced level to meet specialty steel industry needs.	Good—domestic refining capacity has increased to meet recycling needs.
Prospects for substantial reduction in current levels of U.S. dependence by the year 2000 using the above alternatives.	Fair	Good	Fair	Good
Most promising technical routes to reducing U.S. import dependence by 2000	Substitution Recycling Diversification of supplies	Recycling Design, processing, and manufacturing technologies Domestic production substitution	Continuation of conservation trends in steelmaking Diversification of supplies Replacement of steel in some applications by aluminum or plastics	Recycling of automobile catalysts and electronic scrap Domestic production

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[a] U.S. Department of Interior, Bureau of Mines, *Mineral Commodity Summaries 1984* Washington, DC: U.S. Government Printing Office, 1983). Figures on apparent consumption may differ from apparent consumption figures in table A or ch. 1 because of different reporting conventions used in different Bureau of Mines statistical series.

[b] U.S. Department of Interior, Bureau of Mines, *Mineral Commodity Summaries 1983* (Washington, DC: U.S. Government Printing Office, 1982) Estimates of purchased scrap as a percentage of apparent consumption in 1982 are preliminary estimates which may be subject to revision. Appreciable quantities of manganese contained in ferrous and nonferrous scrap and steelmaking slag are recycled. However, scrap recovery specifically to recycle manganese is minimal.

[c] U.S. Department of Interior, Bureau of Mines, *Minerals Yearbook: Vol. I, Metals and Minerals 1982* (Washington, DC: U.S. Government Printing Office, 1983), table 10, pp. 54-55.

[d] U.S. Department of Interior, Bureau of Mines, "Mineral Commodity Profiles 1983" (chromium, cobalt, manganese, and platinum group metals).

SOURCE: Office of Technology Assessment, 1984.

chapter 6 (conservation and recycling) and chapter 7 (substitution and advanced materials).

Chromium

The United States is dependent on South Africa and the Soviet Union for most of its chromium, half of which is used in stainless steels. Major opportunities exist to conserve chromium, especially in nonessential applications for stainless steel where substitutes (e.g., aluminum and plastic) are widely available. For critical applications, some promising lower chromium stainless steels are now under development—primarily by government. These will need substantial additional work before they will be available for use. In some applications, chromium is so essential that a breakthrough in basic research may be needed to find substitutes. Although recycling of stainless steel scrap has reached a high level, reduced downgrading and improved recovery of obsolete scrap and steelmaking wastes could help add to chromium supplies. Because known domestic chromite deposits are very poor in quality, diversification of foreign suppliers may be a more attractive option than development of known domestic chromite deposits. Discovery of higher quality domestic chromite deposits appears unlikely but cannot be ruled out.

Cobalt

Of the first-tier strategic materials, cobalt offers the greatest range of technical alternatives to current supply patterns, which are dominated by Zaire and Zambia. Ongoing manufacturing trends in the aerospace industry are encouraging highly efficient use of cobalt in the fabrication of jet engine parts, and this trend is likely to continue in the future. With advances in recycling technologies, it should become technically possible to recover much more of the several million pounds of cobalt contained in downgraded scrap or waste that is not recovered each year. Substitutes are already available for cobalt in many applications. In addition, some low- or no-cobalt substitutes have been developed which could replace cobalt in some superalloys—the application of greatest concern because of their importance in jet engines. These will need to be thoroughly tested and qualified for use before they can be employed. Over the long term—beyond the year 2000—promising advanced materials may increasingly be used in jet engines, potentially reducing the need for superalloys (and hence strategic materials) in this critical application.

Evaluations of known domestic deposits suggest that more than 10 million pounds of cobalt could be produced annually for a 15- to 20-year period if the four most promising sites were developed simultaneously. At current cobalt prices, none of these sites would be profitable to develop. Moreover, at some sites, cobalt would be a coproduct or byproduct of other metals production so that production economics would not depend on cobalt alone. Federal subsidies, such as a guaranteed purchase price, would probably be needed for a protracted period for sustained cobalt production to occur.

Manganese

Options for reducing U.S. reliance on the Soviet Union and South Africa for manganese supplies are largely limited to conservation in steelmaking and developing greater diversity among foreign suppliers. The ongoing process of upgrading U.S. steelmaking facilities and processes should make it possible to reduce total manganese requirements (excluding home scrap) for each ton of steel from about 36 to 25 pounds by the year 2000. Manganese ferroalloy requirements, especially, could be reduced—falling from about 16 to about 8.3 pounds per ton by the year 2000. A commitment to changing supply patterns to reduce reliance on South Africa and the Soviet Union could also reduce U.S. vulnerability, since several other major foreign producers exist. As with chromium, virtually no exploitable domestic manganese deposits are known at this time. Unless a major new deposit is found, prospects for significant domestic production will remain slight.

Platinum Group Metals

Alternatives for reducing U.S. dependency on South Africa and the Soviet Union for platinum group metals (PGMs) include increased recycling of automotive catalysts and electronic scrap and development of domestic PGM deposits. Between now and 1995, the annual amount of potentially recoverable PGM from scrapped cars will grow from about 110,000 to 700,000 troy ounces or more. If 500,000 troy ounces of this were to be recycled, an amount of PGM equivalent to 25 percent of 1982 U.S. PGM consumption for all uses would be added to U.S. supplies. PGMs are of such high cost that they are used very efficiently, and the incentive for conservation is high. The United States also has one of the world's most promising deposits of PGM that has yet to be exploited in the Stillwater Complex of Montana. One mine site in the complex is now being evaluated for possible production, raising the possibility of appreciable domestic production by the end of the decade. Initial plans call for production of about 175,000 troy ounce of PGM, about 9 percent of total U.S consumption in 1982. Over the long term, much higher production levels may be achievable if additional sites within Stillwater and elsewhere are brought into production.

Existing Laws and Strategic Materials Policy

There are many ways in which the Federal Government can assist and guide the private sector in implementing the aforementioned technical approaches if it chooses. Options range from dissemination of information and data, to sponsorship of research and development (R&D), to provision of incentives and subsidies to encourage private actions. Over the years, congressional concern about strategic materials has led to adoption of several laws which provide a relatively comprehensive statutory framework for Federal activities of this kind. Laws such as the Defense Production Act and the Strategic and Critical Materials Stockpiling Revision Act provide basic authorization to undertake a full panoply of activities related to strategic materials, such as development of substitutes, development of processing technologies, and development of domestic production capabilities when such activities are deemed necessary for national security or would help achieve stockpile objectives.

Two recent Federal laws have emphasized the need for high-level executive branch policy coordination of strategic materials R&D activities. The National Critical Materials Act of 1984 directed the establishment of a National Critical Materials Council in the Executive Office of the President to assist in executive branch strategic material policy formulation and coordination, and oversee a new Federal advanced materials R&D program. The 1980 National Materials and Minerals Policy, Research and Development Act placed increased emphasis on materials R&D in the Federal Government, and articulated a national materials policy. Table 8-2 compares the potential contribution of the technical alternatives to material supplies with the degree of government action that may be needed to achieve that contribution, while major Federal laws that provide potential vehicles for implementing these actions are discussed briefly below.

National Materials and Minerals Policy, Research and Development Act (Public Law 96-479)

In 1980, Congress enacted the National Materials and Minerals Policy, Research and Development Act to provide a basic coordinating framework for executive branch material policy decisions. The law gave heightened visibility to substitution, recycling, and conservation as well as to mineral development to meet U.S. material policy objectives, and emphasized the importance of government support for R&D in addressing material problems. A key purpose

Table 8-2.—Probable Degree of Government Involvement Needed in Long-Term Strategies to Reduce Vulnerability

Material alternative	Potential contribution to reduced vulnerability	Extent of government action needed to achieve potential	Nature of government actions			Likely time-frame to achieve outcome once action initiated
			Information and monitoring	Research and development	Direct subsidy to implement alternative	
Chromium:						
Recycling	Large	Moderate	X	X	No	Near-term
Substitution:						
Noncritical applications	Large	Moderate	X	Possibly	No	Medium-to long-term
Critical applications	Medium	Moderate to extensive	X	X	No	Long-term
Supply diversity	Small to medium	Extensive	X	Possibly	Probably	Long-term
Domestic production	Small, without new discoveries	Extensive	X	X	X	Long-term
Cobalt:						
Recycling and conservation	Large	Moderate to extensive	X	X	Probably not	Near-to medium-term
Domestic production	Large	Extensive	X	X	X	Near-term
Substitution	Medium	Moderate to extensive	X	X	Possibly	Medium-to long-term
Supply diversity	Medium	Extensive	X	Possibly	Probably	Long-term
Manganese:						
Conservation	Large	Modest	X	X	No	Near-to medium-term
Supply diversity	Large	Extensive	X	Possibly	X	Long-term
Domestic production	Small	Extensive	X	X	X	Long-term
Substitution	Small	Not assessed	?	?	?	?
Platinum group metals:						
Recycling and conservation	Large	Modest	X	Minor	No	Near-term
Domestic production	Medium to large	Probably modest	X	Minor	Probably not	Near-term (possible)
Substitution:						
Noncritical applications	Large	Modest	X	No	No	Near-term
Critical applications	Probably small	Not assessed	?	?	?	Long-term
Supply diversity	Probably small	Not assessed	?	?	?	Long-term
Advanced materials:						
Ceramics	Potentially large	Extensive	X	X	Possibly	Long-term
Composites	Potentially large	Extensive	X	X	Possibly	Long-term

KEY:
Large—20% or more of 1982 U.S. consumption.
Medium—5 to 20% of 1982 U.S. consumption.
Small—less than 5% of 1982 consumption.

Near-term—within 5 years.
Medium-term—within 15 years.
Long-term—beyond 2000.

Modest—Little required beyond current level.
Moderate—Some new actions needed.
Extensive—Major new actions required.
X = Increased activities in this area.
? = Not assessed.

SOURCE: Office of Technology Assessment.

of the Act was to provide better mechanisms for coordinating Federal material-related programs, which presently are highly decentralized, being administered by a host of agencies with differing missions, objectives, and perspectives.

The Act declared that "it is the continuing policy of the United States to promote an adequate and stable supply of materials necessary to maintain national security, economic wellbeing and industrial production with appropriate attention to a long-term balance between resource production, energy use, a healthy environment, natural resources conservation and social needs."[1]

The 1980 Act encompassed all materials that are related to industrial, military, and essential civilian needs. However, strategic materials were given high visibility in the Act, which defined materials as:

> . . . substances, including minerals, of current or potential use that will be needed to supply the industrial, military and essential civilian needs of the United States in the production of goods or services, including those which are primarily imported or for which there is a prospect of shortages or uncertain supply, or which present opportunities in terms of new physical properties, use, recycling, disposal or substitution . . .[2] (The definition excludes food and energy fuels.)

The law also called on the President to submit to Congress, on a one-time basis, a "program plan" containing such existing or prospective proposals and executive branch organization structures "as he finds necessary" to implement key sections of the Act.

In April 1982, President Reagan submitted to Congress his materials and minerals program plan required by the Act. The 22-page document summarized actions to be taken in four major areas—land availability, materials research and development, minerals and materials data collection, and the strategic and critical materials stockpile.[3] The plan assigned responsibility for coordination of national materials policy to the Cabinet Council on Natural Resources and the Environment. R&D coordination not involving policy questions was assigned to the interagency Committee on Materials (COMAT), under the direction of the White House Office of Science and Technology Policy (OSTP) Federal Coordinating Council on Science, Engineering, and Technology.

Several concerns have been expressed about the Administration's discharge of its responsibilities to Congress under the 1980 Act. The Act required the plan, as a minimum, to contain a program, budget, and organizational structure for "continuing long-range analysis of materials use to meet national security, economic, and social needs." The plan refers to a review of the Federal minerals and materials data system, but makes no specific reference to establishment of a continuing long-range analysis of materials, and also did not provide a budget proposal.

The President's plan also drew criticism for overlooking some key areas of emphasis in the Act. The report focused primarily on minerals availability issues associated with Federal lands and on the management of the stockpile; substantially less emphasis was given to the R&D components of the 1980 Act. Nor did it address recycling, conservation, and substitution in detail. Although the Act provided the President with substantial discretion to select plan components, critics contended that the failure to address these issues made the President's plan inadequate to fulfill the intent of the Act.

Other implementation difficulties were identified by the U.S. General Accounting Office (GAO) in a 1984 report to Congress on overall executive branch responses to the law.[4] GAO pointed out that not all agencies with important materials responsibilities were represented on the Cabinet Council on Natural Resources and the Environment, charged with overall policy coordination. Additionally, GAO found that some agencies have made key materials policy decisions independent of council clearance.

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[1] Public Law 96-479, sec. 3.

[2] Public Law 96-479, sec. 2(b).

[3] The White House, National Materials and Minerals Program Plan and Report to Congress (Washington, DC: N.P.) April 1982.

[4] U.S. General Accounting Office, *Implementation of the National Minerals and Materials Policy Needs Better Coordination and Focus* (Washington, DC: U.S. General Accounting Office, Mar. 20, 1984), GAO/RCED-84-63.

The effectiveness of COMAT in providing information for R&D policy decisions was questioned. According to GAO, the President's fiscal year 1984 budget included an unexpected $38 million for a major new initiative in materials sciences research by the Department of Energy's (DOE) Lawrence Berkeley Laboratory in which COMAT and even the Cabinet Council had little input. The overall goal of this initiative was to improve linkages among academic, national laboratory, and industry scientists for the future advancement of high-technology industries—a responsibility the President's plan delegated to COMAT. However, the policy decision concerning redirection of Federal materials R&D and the appropriateness of DOE's initiative were made independently by the Director of OSTP before COMAT had formulated a position on the need for a new initiative. Moreover, the Cabinet Council had not reviewed the need for this program, nor had it been developed within the context of an overall national materials and minerals R&D program. Another instance cited by GAO was the failure by the Department of Defense to coordinate with the Cabinet Council before seeking funds to subsidize domestic mineral production capacity under Title III of the Defense Production Act.

Several strategic materials reports required by law either have been submitted late or not at all. First, Congress mandated OSTP to prepare and annually revise "an assessment of national material needs arising from scientific and technological concerns over the next 5 years" and where possible, over the next 10 or 25 years. As of March 1984, the initial report had not been done, and the office informed GAO that it had no plans to undertake the study. (The law did not specify a date for submitting the report.)

The Department of Defense told GAO that it had prepared a report "assessing critical material needs related to national security" and "steps necessary to meet those needs" which was required by the Act." However, the report was required to be submitted to Congress by October 21, 1981. As of March 1984. the report had not been submitted, apparently because it was still under review by the Administration. A Department of the Interior report, also due in October 1981, was not submitted until November 1983. Only the Commerce Department complied fully with the Act. (A more detailed summary of GAO's findings can be found in box 4-A in ch. 4.)

Despite the Administration's failure to fullfill the information needs of Congress, many individual agencies appear to be carrying out their own activities in a way that is reasonably responsive to the law. Strategic materials R&D funding has fared well in a time of budget cuts, and many other initiatives have been undertaken that were not specifically identified in the President's plan. For example, in 1984, the Secretary of the Interior, who also serves as Chairman of the Cabinet Council on Natural Resources and the Environment, created a National Strategic Materials and Minerals Program Advisory Committee.

National Critical Materials Act of 1984 (Public Law 98-373)

Signed into law by President Reagan on July 31, 1984, Title II of Public Law 98-373 establishes a statutory National Critical Materials Council "under and reporting to" the Executive Office of the President to advise and assist the President in formulating critical material policies. The Council is also given key responsibilities in developing a "national Federal program" for advanced materials research and technology, and stimulating innovation and technology utilization in basic and advanced materials industries.

Authorization for Title II will expire on September 30, 1990, unless extended by Congress. The three members of the Council are to be appointed by the President, with advice and consent of the Senate if the appointee is not already a Senate-confirmed government official. One member is to be designated Chairman of the Council by the President. In selecting members, particular emphasis is to be given to people with training, experience and achievement in materials policy, science or engineering, and at least one member is to have a background and understanding of environmental issues. The Council is directed to appoint a full-time Executive Director, who is authorized to employ a staff of up to 12 people in carrying out the Council's duties under the act, and develop, subject to Council approval, rules and regulations needed to carry out the Act's purposes. The law authorizes the appropriation of $500,000 for fiscal year 1985, and thereafter, such sums as may be necessary. As mentioned, Title II authorities will expire at the end of fiscal year 1990 unless specifically extended by Congress.

The Council, among other things, will: 1) assist in establishing responsibilities and provide for coordination and implementation of critical materials policies (including research and technology) among Federal agencies; 2) bring materials issues deemed critical to the Nation's economic and strategic health to the attention of the President, Congress, and the general public; and 3) ensure continuing consultation with the private sector in matters related to critical materials; materials research, development, and use; and Federal materials policies.

In accomplishing these responsibilities, the Council is to review and appraise Federal agency programs to determine the extent to which they contribute to achieving the policy and directions given by the 1980 National Materials and Minerals Policy, Research and Development Act. It is also to be involved in recommending budget priorities to the Office of Management and Budget (OMB) for materials activities by each Federal agency and department.

By April 1, 1985, the Council was to submit to Congress a report on critical materials inventories, and prospective needs for these materials by government and industry. One component of this report is to be a long-range assessment, prepared in conjunction with OSTP, on prospective critical materials problems, and to advise about how to address these problems. The Council is to review and update its report and assessment as appropriate, and is to report to Congress at least biennially. The Council is also to recommend to Congress changes in current policies, activities, and regulations, as well as new legislation, needed to achieve the intent of Public Law 98-373, and Public Law 96-479.

The Council is given a major role in developing and overseeing the national Federal program for advanced materials research and technology called for by the Act. It is to establish a Federal program plan for R&D in this area, identifying responsibilities for carrying out the research and providing for coordination among the Office of Management and Budget, the Office of Science and Technology Policy, and other appropriate agencies and offices. The Council is to annually review, and to report to Congress, on the Federal R&D plan.

The Council is to annually review the materials research, development, and technology authorization requests and budgets of all Federal agencies to ensure close coordination of program goals and directions with policies determined by the Council. The Office of Management and Budget is to consider authorization requests in these areas as an "integrated, coherent, multiagency request" to be reviewed by the Council and OMB for its adherence to the national Federal materials program plan in effect for that fiscal year.

To promote innovation in the basic and advanced materials industries, the Council is to evaluate and make recommendations about establishing Centers for Industrial Technology as provided for by the Stevenson-Wydler Technology Innovation Act of 1980, which is discussed subsequently. The activities of such nonprofit centers, initially funded by Government but intended to become self-sufficient after 5 years, would focus on generic materials research.

The Council is directed to establish, in cooperation with other agencies and private industry, a mechanism for the efficient and timely dissemination of materials property data. This is intended to promote innovation and better use of materials in design. Possible establishment of a computerized material property data system (using existing resources to the extent practicable) is to be considered.

Public Law 98-373, like Public Law 96-479 before it, is in many respects process-oriented legislation, intended to give the Executive Office of the President key responsibilities for critical materials policy. Within the framework established by the law, the executive branch is given considerable discretion and flexibility to establish goals, objectives, and priorities for critical and advanced material programs. The law, for example, does not specifically define the terms "advanced materials" and "critical materials," but instead uses the broad definition of materials provided by Public Law 96-479.

Defense Production Act (50 U.S.C. 2061 et seq.)

Enacted in 1950, the Defense Production Act (DPA) provides several mechanisms for assuring availability of materials and industrial capabilities needed for the national defense. Title I authorizes government priorities for allocation of materials in a congressionally or presidentially proclaimed national emergency or war.

Title III authorizes the President to support private activities which would expedite "production and deliveries or services" in aid of national defense. Loans and loan guarantees are authorized for expansion of capacity, development of technological processes, or the production of essential materials, including exploration, development, and mining of strategic metals. Purchases and purchase commitments are authorized for metals, minerals, and other materials for government use or resale. The President is also authorized to "make provision for the development of substitutes for strategic and critical materials" when "in his judgment it will aid the national defense." Materials considered excess to DPA requirements can be transferred to the national stockpile. Title III assistance can be used both domestically and abroad.

In its 1984 reauthorization of DPA (Public Law 98-265), Congress established new procedures for authorization of Title III projects which apply when a congressionally or presidentially declared national emergency is not in effect. Among other things, the law requires the President to determine that federally supported projects meet essential defense needs and that the Federal support offered would be the most "cost-effective, expedient, and practical alternatives for meeting the need." The law requires "industrial resource shortfalls" for which Title III assistance is sought to be identified in the budget (or budget amendments) submitted to Congress. If more than $25 million in aggregate Federal assistance would be entailed to meet the industrial resource shortfall, specific authorization by law would be required.

Historically, DPA has been used primarily to encourage mining of strategic minerals in this country and abroad. The instruments provided in the law, however, could potentially be used for development of substitutes, advanced recycling technologies and other technical innovations considered desirable for national security. In addition, DPA is now viewed as a means to secure supplies and essential processing capabilities for advanced materials needed for defense purposes.

Strategic and Critical Materials Stock Piling Revision Act (Public Law 96-41)

In 1979, Congress revised and updated prior laws related to the National Defense Stockpile through enactment of Public Law 96-41. The law resolved several issues related to changing executive branch strategies for stockpile management among successive administrations. Among other things, it stated that the stockpile was for the purpose of national defense only, and established a statutory stockpile goal of having a 3-year supply of materials on hand to meet national defense, industrial and essential civilian needs in a national defense emergency or war. It also established a stockpile transaction fund so that sales of excess materials could be used to acquire new materials consistent with stockpile goals.

Several provisions in the Stockpile Revision Act have indirect relevance to government support of private activities related to strategic materials. The law calls for maximum feasible use of competitive procedures for stockpile acquisitions; however, waivers are authorized, and this could provide a basis for supply diversification on an ad hoc basis.

The law authorizes upgrading of already stockpiled materials through refining and processing so that they will be in the form most suited to current needs. This has prompted the considerable interest of domestic processors. A panel of the American Society for Metals (ASM), for example, recommended in August 1983 that sufficient quantities of substandard cobalt from the stockpile be provided to industry in order that it could test capabilities to upgrade the material to current standards.[5] Of the 46 million pounds of cobalt in the stockpile, 40.8 million pounds were acquired in the 1947-61 period. More stringent requirements and consumer specifications have made much of this cobalt inadequate to meet today's demanding requirements for many critical applications unless the cobalt is upgraded. The ASM panel recommended pilot tests with cooperating private firms to identify preferred procedures to upgrade the cobalt quality so that it could be used immediately in a crisis. The recommendation is under consideration by the General Services Administration (GSA) and Federal Emergency Management Agency (FEMA).

As in the prior stockpiling law, the 1979 Act calls on the President to make "scientific, technologic and economic investigations" concerning "development, mining, preparation, treatment and utilization of ores and other mineral substances . . ." These investigations, delegated by the President to the Secretary of the Interior, are to be carried out to determine and develop "new domestic supply sources; devise methods for treatment and use of lower grade ores and mineral substances; develop substitutes for essential ores and minerals." Investigations may be carried out on public lands, and with the consent of the owner, on private lands "for the purpose of exploring and determining the extent and quality of deposits of such minerals, the most suitable methods of mining and beneficiating such materials, and the cost at which the mineral or metals may be produced."[6]

Stevenson-Wydler Technology Innovation Act of 1980 (Public Law 96-480)

The Stevenson-Wydler Act is intended to promote development and diffusion of new industrial technologies in the United States. The law gives the Secretary of Commerce, in cooperation with other relevant agencies, key responsibilities in stimulating transfer and diffusion of information about federally funded technology development to the private sector and to State or local governments. It requires each Federal laboratory to establish an Office of Research and Technology Applications to facilitate information transfer about activities within the lab that have potential for successful application by industry. In addition, the law established a central Federal clearinghouse (called the Center for Utilization of Federal Technology) to collect and disseminate information about federally owned or originated technologies. (This function has been assigned by the Commerce Department to the National Technical Information Service.)

The Act also directed the Secretary of Commerce to assist in the establishment of "centers for industrial technologies"—centers affiliated with university or nonprofit institutions set up to enhance technological innovations. The Reagan Administration, on November 17, 1983, revoked rules for making grants for such centers. At the same time, it also promulgated rules for a program for promotion of private sector industrial technology partnerships, indicating that this program was intended to supercede the generic technology center program.[7] The new Administration program provides information support to industrial technology partnerships and cooperative R&D arrangements of corporations, nonprofit organizations, and government.

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[5] American Society of Metals, *Quality Assessment of National Defense Stockpile Cobalt Inventory*, prepared for the Federal Emergency Management Agency (Metals Park, OH: American Societies of Metals, 1983).

[6] Public Law 96-41, sec 8(a). This provision is a continuation of similar provisions in prior stockpiling laws.

[7] *Federal Register*, vol. 48, No. 223, Nov. 17, 1983, p. 52289.

The Stevenson-Wydler Act also directed the National Science Foundation (NSF) to assist in the support of "centers for industrial technology" under the Act. According to a 1984 Administration report on implementation of Public Law 96-480, NSF's previously existing program of support for university/industry cooperative research centers is being used to meet the requirements of the Act in this respect.[8]

The newly enacted National Critical Materials Act of 1984 directs the National Critical Materials Council established by this law to evaluate and make recommendations about establishment of Centers for Industrial Technology to promote innovation and increased productivity in basic and advanced materials industries. Among the activities identified for possible Center involvement were corrosion, welding and joining of materials, advanced processing and fabrication technologies, microfabrication, and fracture fatigue.

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[8] Secretary of Commerce, *The Stevenson-Wydler Technology Innovation Act of 1980*, Report to the President and Congress (Washington, DC: U.S. Department of Commerce, February 1984). According to the report, which was required by Public Law 96-480, the National Science Foundation, in fiscal year 1983, was supporting eight university/industry centers, including two centers on polymers, one on ceramics, and one on welding.

Formulation of Strategic Materials Policy

In formulating long-term technical strategies for reducing import dependency, the full range of available options, on a material-by-material basis, must be considered. In some instances, there may be several options available for each material. These options could potentially ease import vulnerability, but entail different costs and different levels of security. In the case of cobalt, import vulnerability could be reduced in several ways, including domestic production, recycling, and substitution. Domestic production, for example, could make a major contribution to domestic cobalt supplies, with complete supply security, but only at a cost to the government (at 1983 prices) far higher than simply purchasing cobalt for the stockpile from world markets. Other options, such as developing promising recycling technologies to the point where they could be used by industry would cost less, but would also entail greater risk, since it cannot be certain that a given research technology will be commercially viable. It is noteworthy that the implementation of these and other technical approaches to reducing cobalt import vulnerability all entail increased government support.

In other instances, as in the case of PGMs, substantial long-term reductions in import vulnerability may be achievable with little government action. Private industry is already well-positioned to take advantage of the growing inventory of PGMs that could be recycled from automotive catalysts as cars are scrapped; and, with some limited increase in PGM prices, nearly 10 percent of current domestic needs could be provided from one U.S. site, with additional production possible from other sites in the longer term. Continued monitoring of industry trends will be needed, but unless one assumes that a PGM supply disruption is likely in the near term, government action to encourage recycling or domestic production is probably not needed at this time.

Experience has shown that development of overall Federal strategies to reduce import vulnerability is a highly complex task. Several Federal agencies have important research responsibilities in the materials field, including the Departments of Defense, Interior, Energy, and Commerce; and the National Aeronautics and Space Administration (NASA). FEMA has lead agency responsibility for coordination of stockpile planning, and GSA administers it. Many other Federal departments and regulatory agencies have indirect effects on materials policy through tax policies, regulation of commerce, environmental protection, Federal land management, antitrust enforcement, patent policy, foreign affairs and trade policy, and other activities. (Selected executive branch agencies with direct responsibilities for strategic materials are shown in table 8-3.)

This decentralization is, to a certain extent, unavoidable, and may even be desirable, but it has made the job of formulating strategic materials policy difficult for both Congress and the executive branch. Congress itself has many different committees with jurisdictional areas related to strategic materials, including (among others) House Committees on Armed Services; Banking, Finance, and Urban Affairs; Science and Technology; and Interior and Insular Affairs; and Senate Committees on Armed Services; Banking, Housing, and Urban Affairs; Commerce, Science, and Transportation; and Energy and Natural Resources. Appropriation subcommittees are even more diverse.

Through enactment of the National Critical Materials Act of 1984 and the National Materials and Minerals Policy, Research and Development Act of 1980, Congress has firmly placed statutory responsibility for coordinating Federal agency activities and decisionmaking with regard to strategic materials research in the Executive Office of the President. The policy planning and coordination procedures required by the 1980 Act, together with the statutory establishment of the National Critical Materials Council "under and reporting to" the Executive Office of the President by the 1984 Act, may in time provide coordinated and coherent strategies to guide Federal agency activities to reduce import vulnerability.

As the Administration begins to implement its new mandate, congressional oversight of the Administration's progress in the continuing implementation of both the 1980 and 1984 laws will be important. Both laws give the Administration considerable flexibility and latitude in developing strategies to address strategic materials issues. They are oriented towards development of effective processes to formulate, coordinate, and implement materials policy programs, and by and large do not dictate substance. This flexibility could lead to highly innovative initiatives in the materials field, but it also means that continuing congressional guidance may be needed at times to assure that the intent of the the two laws is met.

OTA's analysis of oversight issues has focused on two specific issues that may be particularly relevent as the Administration begins to implement the 1984 Act: establishing policy goals, objectives, and priorities for strategic materials, and upgrading information about Federal strategic materials R&D activities as a key step in interagency coordination. These issues are discussed below and are summarized in table 8-4.

Goals, Objectives, and Priorities of Strategic Materials Policy

A long-term commitment is needed if technical approaches to the reduction of strategic materials vulnerability are to succeed. Moreover, the combination of technical approaches effective for one material will often be inappropriate for another. Recognition that effective planning and policy formulation procedures by the executive branch were needed to develop coordinated goals, objectives, and strategies for materials research led to enactment of the National Materials and Minerals Policy, Research and Development Act of 1980. However, the expectation that this law would lead to an effective policy structure for coordination of strategic material activities throughout the government has not been fully realized, as has been discussed.

With adoption of the National Critical Materials Act of 1984, prospects for improving the executive branch policy structure will hinge to a considerable extent on the effectiveness of the new National Critical Materials Council in the Executive Office of the President. Section 205(a) of the law gives the Council "specific responsibility for overseeing and collaborating" with Federal agencies and departments "relative to materials research and development policies and programs." In this role, the Council is mandated to annually review both the authorization requests and budget proposals of all Federal agencies conducting ma-

Table 8-3.—Selected Federal Agencies With Strategic Material Responsibilities

Agency/department	Policy development						Research and development							Securing material supplies/maintaining domestic processing capabilities				Comments
	Policy coordination	Budget review	R&D coordination	Reports to Congress	Problem assessment	Statutory responsibilities under P.L. 96-479 or P.L. 98-373	Exploration and minerals data	Mining/minerals processing	Materials conservation	Recycling	Substitution	Advanced materials	Material property data	Stockpile management	Emergency allocation	Defense production act incentives	Supply diversification abroad	
Executive Office of the President:																		EOP assigned overall responsibility for policy and R&D coordination by the National Materials and Minerals Policy, Research and Development Act of 1980 (P.L. 96-479). The National Critical Materials Act of 1984 statutorily established the National Critical Materials Council to assist and advise the President on critical materials and advanced materials policy (P.L. 98-373).
Cabinet Council and Natural Resources and Environment	X																	
Office of Science and Technology Policy			X	X	X	X												
Office of Management and Budget		X				X												
(National Critical Materials Council)	X	X	X	X	X	X	—Coordinates R&D—											
Department of Commerce				X	X	X								X	X	X		**Under P.L. 95-479, DOC has statutory responsibility, assigned to the Office of Strategic Resources, for preparing case studies of material problems**
National Bureau of Standards									X	X	X	X	X					
Department of Defense and Individual Services				X	X	X			X	X	X	X	X	X	X	X		P.L. 96-479 required DOD to submit a Congressional report on National Security needs for materials by Oct. 21, 1981. As of March 1984, the report was still under administration review
Department of Energy and National Laboratories									X	X	X	X	X			X		
Department of the Interior			X		X	X												The Secretary of Interior serves as Chairman of the Cabinet Council and Natural Resources and Environment, assigned overall policy responsibility for strategic materials by President Reagan. The Secretary has established an advisory panel on strategic materials to assist the Department in its strategic material programs.
Bureau of Mines							X	X	X	X	X	X					X	
Geological Service							X	X									X	
National Aeronautics and Space Administration									X	X	X	X	X			X		
Federal Emergency Management Agency				X			—Supports R&D—							X	X	X	X	FEMA is a lead coordinating agency in stockpile management policy
General Services Administration				X										X	X	X	X	**GSA administers the stockpile**
National Science Foundation					X		—Supports R&D—											
International Development Cooperation Agency																	X	
Export-Inport Bank																X	X	

SOURCE: Office of Technology Assessment.

Table 8-4.—Policy Alternatives for Formulation of Strategic Materials Policy

		Arguments for/against	
Problem/issue	Option	Positive	Negative
1. The executive branch has had difficulty in establishing overall goals, objectives, and priorities for strategic materials R&D policy. As a result, Federal agency activities are not guided by a coherent, overall strategy for long-term reduction in import vulnerability.	Direct the National Critical Materials Council established by Public Law 98-373 to develop a long-term strategy for Federal strategic materials activities, including goals and objectives by which individual agency activities can be monitored. The multiyear strategy could be revised on a 4-year basis by the Executive Office of the President, giving Congress the opportunity to review progress, provide guidance and clarification as needed.	Clear direction for strategic materials policy and long-range plans to address specific material needs is required to give continuity and ensure appropriate follow-through for strategic material research.	Overly specific congressional guidance could result in inflexible agency response. Periodic revision of the overall strategic materials plan could lead to excessive time and expenditures devoted to policy formulation and planning activities.
2. Federal R&D activities related to strategic materials are dispersed over a large number of agencies. To coordinate R&D policy, conduct oversight and establish priorities, improved survey information is needed.	Instruct the National Critical Materials Council to give high priority to section 209(a)(3) of Public Law 98-373 which calls for cataloging R&D activity as fully as possible. Such a catalog, if undertaken on a material-by-material and objective-by-objective basis, with updates on a regular schedule, would be useful in the budget review activities of the council and would help identify progress towards meeting goals.	Would give decisionmakers information needed to monitor multi-agency responses to overall strategic material goals, identify areas of overlap or duplication of effort, and areas where insufficient R&D is conducted.	Could lead to overemphasis on strategic materials R&D to the detriment of other needed materials research in agency R&D program planning.

SOURCE: Office of Technology Assessment.

terials R&D to "ensure close coordination of the goals and directions of such programs with the policies determined by the Council." This process is to be coordinated with the Office of Management and Budget, which is to consider material budget proposals as a coherent multiagency request. The new law requires the Council to prepare and annually revise a Federal program plan for advanced materials R&D.

It seems unlikely that the Council will be able to succeed in its coordinating functions unless it is able to articulate overall goals, objectives, and priorities that could guide strategic materials R&D policy. One important question is whether Federal research objectives should be set broadly—i.e., strategic materials in general—or should be targeted as closely as practical to those materials considered to be most vulnerable. By and large, the approach taken over the years, and which still prevails, is to address strategic materials in a generic sense. This allows agencies to adopt a flexible approach in their research programs, but without centralized administration guidance, it also results in diffusion of efforts among many materials.

An alternative approach would be for the Council to give greatest priority to those materials that are most vulnerable to a supply disruption and most critical to the United States.

Such an approach presents some problems. First, one cannot know in advance which materials will actually be subject to a supply disruption, so a danger exists that the wrong materials will be targeted. Inflexible administration and rigid adherence to outdated objectives and strategies could also be potential problems. Furthermore, much materials research is not specific to individual metals, and such research might not receive support if forced into a material-by-material evaluation in determining support for R&D activities. However, viewed as a policy tool for establishing overall Federal goals and objectives and for selecting among alternative strategies for achieving them, the material-specific approach could give a clearer sense of direction to Federal efforts to combat materials vulnerability.[9] An effective strategy, therefore, might very well involve a combination of both the generic and material specific approaches to achieve the objective of reduced import vulnerability.

Federal program planning for strategic materials needs to reflect long-term objectives, while still being adaptive and flexible in light of changing circumstances. The 1984 Act's budget review mechanism in theory provides a vehicle for infusing a longer term perspective into agency planning than is provided by the annual budget-setting process.

This connection is most explicit in the case of advanced materials R&D, through Public Law 98-373's requirement that the Council develop and annually revise a Federal program plan for advanced materials research and technology. The law itself does not specify the components of this plan, nor does it specifically define the term "advanced materials." However, the House Committee on Science and Technology, in its report on the bill, indicated its intention that the plan include at least four elements, including "a listing of major existing Federal material research and technology programs—to include existing funding and goals as well as proposed funding levels over the next 5 years." Other plan elements identified by the Committee were: "an assessment of current national materials research and technology needs and problems . . . identification of priorities for research to address those needs or problems," and "recommendations for program initiatives and changes to meet policies and goals as set forth by the Council."[10]

While the law may not explicitly require such a plan for strategic materials R&D, such an approach might well be effective should the Council choose to pursue it. If a more active congressional role is desired, one option (table 8-4, issue 1) would be for the executive branch to prepare and submit to Congress a multi-year strategic materials plan of action on a periodic basis—say once every 4 years. Congress would then have the opportunity to review the plan's goals and objectives, along with specific measures and estimated funding levels needed to achieve them.

The multi-year plan could then serve as a kind of benchmark by which the Council and Congress could evaluate annual budget requests with respect to strategic materials R&D activities. In reviewing the plan, Congress could give the Council and the Executive Office of the President—which have overall responsibility for materials coordination—additional guidance on specific issues related to the multi-year plan.

Structured into the Act is considerable opportunity for congressional review and oversight of the Council's activities, through its biennial reporting on critical materials to Congress, its annual reporting to Congress on the national Federal advanced materials program plan, and its charge to recommend, when appropriate, changes in current policies, activities, and regulations, and additional legislation that may be needed to carry out materials policy.

In the end, the selection of a framework for policy formulation depends on the extent to which Congress wishes to be involved in setting the overall direction, goals, and objectives for strategic materials policy, and the extent to which it wishes to delegate that function to the executive branch. Establishment of the National Critical Materials Council, and the continuing planning processes required by the 1980 Act, clearly provides legislative authorization for effective policy planning by the executive branch. However, without legislative oversight and guidance when needed, there is no assurance that current or future administrations will fully use these policy tools to effectively formulate executive branch strategic materials policies.

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[9] The need for material specific approaches to reduce export vulnerability has been discussed by the U.S. General Accounting Office, Report to the Secretary of Interior (GAO/EMO-82-69), June 3, 1982.

[10] House Report 98-593, Part I, pp. 38-39.

Providing Information About Federal Research and Development Activities

A sustained program of Federal R&D will be the cornerstone of any long-term strategy to reduce U.S. materials vulnerability using the technical alternatives considered in this report. In the last decade, strategic materials R&D has received increased emphasis, and recent levels of research funds appear to be quite healthy. However, concern exists about the adequacy of current coordination mechanisms at the interagency level, especially as they relate to the formulation of policy.

The Federal Government is the primary sponsor of R&D activities related to strategic materials. It is also the primary sponsor of basic and applied research related to development of advanced materials. This is consistent with the administration's position that Federal support for R&D should focus on high-risk or long-term areas that may not otherwise be addressed by industry.

In fiscal year 1980, about 4 percent ($67 million) of the total Federal materials R&D budget was directed at strategic materials (excluding advanced materials).[11] As shown in tables 8-5 and 8-6, nearly 40 percent of this budget was for chromium research, followed by aluminum, titanium, nickel, and cobalt. Most of this research was conducted or sponsored by DOE national laboratories, the Bureau of Mines, NASA, the National Bureau of Standards (NBS), and various components of the Defense Department.

Fiscal year 1980 was the last year for which the executive branch has published comprehensive information about strategic materials R&D activities on a material-by-material basis. Detailed information of the sort portrayed in the tables have not been issued for subsequent years on a governmentwide basis. However, it appears that strategic materials R&D has not been greatly affected by the general trend toward reduction of research budgets that has affected other areas, although some strategic materials programs (e.g., NASA's conservation of strategic aerospace materials program) have been cut back.

Federally funded R&D has been the driving force behind the development of advanced materials. Total Federal expenditures for structural ceramics R&D were $23 million in fiscal year 1982.[12] By fiscal year 1984, Federal expenditures had grown to over $40 million. Recent figures are not available about composite R&D funding. However, in fiscal year 1980, over $80 million in composites R&D were expended by Federal agencies. Advanced materials R&D activities are undertaken by several Federal agencies, including the Department of Defense, NASA, DOE, NBS, and the National Science Foundation.

A central thrust of both the National Critical Materials Act of 1984 and the National Materials and Minerals Policy, Research and Development Act is to establish a mechanism that would replace ad hoc materials and minerals decisionmaking within the executive branch with a coordinated Federal R&D policy. As mentioned, the President's 1982 materials plan reestablished COMAT under the direction of the Federal Coordinating Council on Science, Engineering and Technology (FCCSET)

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[11] U.S. Department of Commerce National Bureau of Standards, *Survey: Materials Life Cycle Research and Development in the Federal Government Fiscal Year 1980* (NBSIR 81-2359 DOE) (Washington, DC: U.S. Department of Commerce, September 1981).

[12] U.S. Department of Commerce, *A Competitive Assessment of the U.S. Advanced Ceramics Industry* (Springfield, VA: National Technical Information Service, 1984), p. 23.

Table 8-5.—Distribution of R&D Funding for Critical Materials by Materials and by Technology Goal* ($1000)

Technology Element	Substitution	New sources	Reclamation	Life extension	Conservation	Total direct	Total related	Total	Agency†
Chromium	4,546	961	260	20,270	540	26,577	—	30,427	1, 3, 4
	1,060	1,020	270	1,300	200	—	3,850		
Aluminum	—	1,676	—	800	—	2,476	—	10,476	1, 2, 3
	8,000	—	—	—	—	—	8,000		
Titanium	850	301	—	2,370	—	3,521	—	7,831	1, 2, 3, 4
	3,600	—	210	—	500	—	4,310		
Nickel	807	1,662	150	1,100	325	4,044	—	7,793	1, 4
	500	549	470	1,530	700	—	3,749		
Cobalt	670	2,216	150	770	—	3,806	—	5,056	1, 3, 4, 5
	300	520	200	230	—	—	1,250		
Niobium	2,000	212	—	1,400	—	3,612	—	4,182	1, 3, 4
	—	—	70	—	500	—	570		
Platinum	700	537	—	200	380	1,817	—	1,967	1, 3
	—	—	150	—	—	—	150		
Manganese	—	1,059	—	—	—	1,059	—	1,663	3, 4
	400	204	—	—	—	—	604		
Tantalum	—	—	—	1,100	—	1,100	—	1,600	4
	—	—	—	—	500	—	500		
Tungsten	—	527	—	—	340	867	—	1,297	3
	—	230	200	—	—	—	430		
Iron ore	—	840	—	—	—	840	—	1,120	3
	—	—	280	—	—	—	280		
Beryllium	75	—	—	—	—	75	—	175	2
	100	—	—	—	—	—	100		
Gold	—	142	—	—	—	142	—	142	3
	—	—	—	—	—	—	—		
Vanadium	—	125	—	—	—	125	—	125	3
	—	—	—	—	—	—	—		
Direct	9,648	10,258	560	28,010	1,585	50,061	—	73,854	
Related	13,960	2,523	1,850	3,060	2,400	—	23,793		
Totals	23,608	12,781	2,410	31,070	3,985				

*NOTES: Funds may be attributed to more than one goal, where appropriate; upper amounts "direct" program funding for research primarily to indicated category; lower amounts "related" program funding directed to the categories, but with significant potential for impact in the indicated category;

†1. Department of Energy
2. Department of Defense
3. Department of the Interior
4. Department of Commerce
5. National Aeronautics and Space Administration.

SOURCE: U.S. Department of Commerce, *Survey: Materials Life Cycle Research and Development in the Federal Government Fiscal Year 1980* (NBSIR 81-2359 DOE, September 1981). The above table may not reflect all Federal funding of research that affect strategic materials. For example, Department of Defense support for surface modification technologies, near-net shape technologies, and retirement for cause research are not identified in the substitution and conservation columns of the table. These programs could result in savings of chromium, cobalt, nickel and other strategic materials.

for the coordination of Federal materials and minerals R&D activities, directing:

- Assistant Secretary-level representation from the departments and agencies concerned with minerals and materials;
- the incorporation into COMAT of the Department of Defense Material Availability Steering Committee and the Interagency Materials Group;
- establishment of a working panel within COMAT to coordinate Federal R&D on essential materials;
- establishment of a formal mechanism within COMAT for information exchange among agency managers of materials R&D programs; and
- policy resolution of materials R&D questions through the Cabinet Council on Natural Resources and Environment.

Table 8-6.—Distribution of Critical Materials R&D Funding by Stage of the Materials Cycle* ($1000)

	Exploration of resources	Extraction	Processing raw materials	Manufacture and fabrication	Application and utilization	Evaluation of properties	Development of materials	Waste management	Totals
Chromium	151 —	— —	550 —	10,300 420	60,050 100	15,570 —	31,616 300	260 70	118,492 890
Aluminum	121 —	— —	1,555 —	1,000 —	3,000 —	5,000 —	500 —	— —	11,176 —
Niobium	32 —	— —	180 —	2,000 200	3,000 200	1,000 500	4,000 —	— 70	10,212 920
Cobalt	120 30	306 106	825 381	810 420	1,000 113	1,190 100	1,270 530	397 84	5,918 1,764
Titanium	51 —	— —	250 210	300 200	1,000 200	1,000 500	1,050 300	— —	3,651 1,410
Platinum	38 —	— —	500 —	200 —	500 —	1,000 —	680 —	— 150	2,918 150
Manganese	55 30	251 106	50 124	500 —	600 113	1,000 —	300 —	247 288	3,003 661
Nickel	120 30	251 243	660 324	— 200	— 313	500 500	860 230	397 293	2,788 2,133
Lead	92 —	— —	950 —	— —	— —	— —	— —	265 —	1,307 —
Tantalum	— —	— —	— —	100 200	200 200	500 500	200 —	— —	1,000 900
Iron ore	— —	— —	840 —	— —	— —	— —	— —	— 200	840 260
Tungsten	57 —	— —	470 430	— —	— —	— —	125 —	— —	652 430
Direct **Related**	837 90	808 455	6,830 1,469	15,210 1,640	69,350 1,239	26,760 2,100	40,601 1,380	1,568 1,235	101,962 9,588

*NOTES: Funds may be attributed to more than one goal, where appropriate; upper amounts "direct" program funding for research primarily to indicated category; lower amounts "related" program funding directed to the categories, but with significant potential for impact in the indicated category;

SOURCE: U.S. Department of Commerce, *Survey: Materials Life Cycle Research and Development in the Federal Government Fiscal Year 1980* (NBSIR 81-2359 DOE, September 1981).

COMAT was directed to perform an inventory of Federal research and technology activities that would be useful for interagency coordination and for assessing national materials needs and objectives. The data acquired from this inventory would be used by the Cabinet Council to aid in policy decisions pertaining to R&D.

COMAT's report, "Inventory of Federal Materials Research and Technology," was issued in June 1983.[13] Unlike the survey done for fiscal year 1980, funding levels for strategic materials research are not separately addressed or even identified. Nor does the 1983 report group Federal R&D activities by specific material (e.g., cobalt, chromium) or by program objective (e.g., minerals development, recycling). Instead, the 1983 inventory lists overall materials program funding levels for fiscal year 1982 and estimated expenditures for fiscal year 1983 on an agency-by-agency basis. Since the 1983 inventory does not identify strategic materials research activities, it is of virtually no use as a policy tool in the development of material-specific objectives and policies for R&D.

Moreover, COMAT apparently has not taken action to assure that individual agencies keep track of strategic materials research activities on an agencywide basis. COMAT representatives from several Federal agencies were contacted by OTA to determine whether detailed agencywide information on strategic materials funding had been compiled independently for fiscal year 1985. Some agencies provided this information at a relatively detailed level, but one major department was able to provide only a partial answer. In this case, OTA was told that it would take 3 to 6 months to perform a strategic material R&D inventory if given a formal request.

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[13] Federal Coordinating Council for Science, Engineering, and Technology Committee on Materials, *Inventory of Federal Materials Research and Technology: Fiscal Year 1982* (Washington, DC: Executive Office of the President, Office of Science and Technology Policy, June 1983).

It would appear, therefore, that COMAT has not established an effective mechanism to track and report on interagency strategic materials research activities. The need for such information in R&D policy formulation is widely recognized as a key step in establishing effective coordination of all Federal activities related to strategic materials research. In fact, the 1984 National Critical Materials Act calls on the Executive Director of the National Critical Materials Council to catalog, "as fully as possible, research and development activities of the Government, private industry, and public and private institutions" (Public Law 98-373, sec. 209(a)(3)). Such information will indeed be critical if the Council is to effectively exercise its new responsibility for coordination and review of Federal strategic materials activities. Consistent with the premise that the executive branch should have considerable flexibility in formulating materials programs and plans, the Act does not specify a timetable for such catalog activities nor identify its content.

Certainly, if effective coordination of strategic materials research were envisioned, information equivalent in detail to the earlier (fiscal year 1980) survey would be needed. Periodic surveys of this sort would also be needed to develop a multi-year executive branch plan of action for strategic materials. Given the recent difficulties the executive branch has had in developing such survey information, congressional oversight and guidance may be needed if the initial activities of the Council do not give priority to developing a continuing tracking system of this sort (table 8-4, issue 2).

Mineral Production and Processing

Currently, there is virtually no production of cobalt, chromium, manganese, or PGMs from domestic mines.[14] However, prospects are good for platinum and palladium production from the Stillwater Complex in Montana, which could provide about 10 percent of U.S. PGM needs (as a percentage of 1982 consumption) if prices increase somewhat, as well as much larger amounts of PGM if it becomes feasible to open other sites. (The decision whether to go ahead with an initial mining project is expected to be made in 1985.) In addition, more than 10 million pounds per year of cobalt (5,000 short tons) could be provided for a 10- to 15-year period if known domestic cobalt deposits were simultaneously developed. Production will not occur unless cobalt prices rise and are sustained at appreciably higher levels than is now the case, or unless the government provides a substantial subsidy. Domestic prospects for production of chromium and manganese production are not good, owing to the very poor quality of known domestic deposits.

The United States heavily relies on a few countries for its supplies of strategic materials. To some extent, supply diversity could be broadened through greater reliance on other countries which have known deposits of strategic materials. Of the four metals under study, supply diversity is currently greatest for manganese; greater diversity on manganese supplies will probably depend on the willingness of producers in Australia, Mexico, and Brazil to increase production for export markets. In the case of chromium, expanded production in Turkey, Albania, and the Philippines appears to be the primary near-term supply diversification option; in the longer term, limited amounts of chromite may be obtainable from deposit types that are now untapped in the Philippines and New Caledonia. Increased supplies of cobalt may be obtainable from Canada as a byproduct of nickel-copper production. Over the long term, cobalt may be obtained as a byproduct from Pacific-rim nickel laterite deposits when future nickel demand justifies new mine operations. Other than the U.S. Stillwater deposit, significant diversification of platinum supplies seems unlikely. (See table 5-3 of ch. 5 for a country-by-country ranking of supply diversification prospects for each of the first-tier minerals.)

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[14] About 2 percent of apparent domestic consumption of manganese is contributed from manganiferious ore containing less than 35 percent manganese. Platinum group metals have been produced domestically in small amounts as recently as 1982. Larger amounts of manganese and some chromium were produced during the 1940s with considerable Federal subsidy. Substantial amounts of cobalt were produced under Federal subsidy during the 1950s. Cobalt was also produced in small amounts as a byproduct of iron production until 1971.

OTA's analysis of alternative policy actions with regard to minerals production and processing focused on the following areas: potential of intensified exploration assistance to locate new domestic deposits; possible government subsidization of domestic production; targeting of Federal programs to encourage diversification of foreign supply sources; and options for addressing problems associated with declining domestic processing capabilities. The options addressed are summarized in table 8-7 and discussed below.

The emphasis in this assessment is on technological issues. Therefore, political issues associated with competing values for Federal land management are not addressed here. Some Federal lands are under highly restrictive management policies which limit the circumstances and kind of exploration activities that can be undertaken, and these restrictions are seen by some exploration geologists as possibly inhibiting private initiatives to discover new mineral deposits. In general, Federal lands being considered for permanent addition to such restrictive management systems as the National Wilderness Preservation System are given some mineral appraisal prior to designation. The reader is referred to a prior OTA assessment,[15] in which alternative alternative management strategies and policy issues associated with mineral development on Federal lands were comprehensively addressed, as well as several other, more recent publications addressing mineral development issues and Federal lands.[16]

Exploration for Domestic Strategic Resources

The outlook for the discovery of commercial-scale deposits of the first-tier strategic materials in the United States is generally agreed to be insufficient to generate more than minor interest by most mineral developers. The U.S. Government spent considerable effort during and after World War II in seeking high-grade domestic deposits of manganese and chromium, with only subeconomic deposits to show for its efforts. Cobalt, while not sought directly, has only been found in low grades and only as a result of exploration for nickel, copper, lead, and zinc. Platinum, the one successful case of discovery of a commercial-grade deposit of a first-tier material, is quite limited in terms of total U.S. demand for PGMs.

Past failures, however, do not mean that there is no possibility of discovering domestic deposits of chromium, cobalt, manganese, or PGMs. Past experience, however, makes exploration less attractive for these materials than

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[15] U.S. Congress, Office of Technology Assessment, *Management of Fuel and Nonfuel Minerals in Federal Lands*, OTA-M-88 (Washington, DC: U.S. Government Printing Office, April 1979).

[16] Legislative status of selected bills in the 98th Congress relating to strategic minerals evaluation and Federal lands is provided in *Strategic Materials Management*, June 15, 1984. Procedures used in regional mineral appraisals on Federal lands are discussed in John J. Schanz and John G. Ellis, *Assessing the Mineral Potential of the Federal Public Lands* (Washington, DC: U.S. Library of Congress, Congressional Research Service, 1983). Recent Department of Interior activities related to Federal land mineral evaluation potential are discussed in U.S. Department of the Interior, *Summary Report: U.S. Bureau of Mines Department of Interior Programs and Studies Required by the National Materials and Minerals Policy Act of 1980 (Public Law 96-479)* (report submitted to the chairman of the Subcommittee on Transportation, Aviation, and Materials, U.S. House of Representatives Committee on Science and Technology, with cover letter dated Nov. 10, 1983).

Table 8-7.—Policy Alternatives for Exploration, Mineral Production, and Processing

		Arguments for/against	
Problem/issue	Option	Positive	Negative
1. Lack of industry interest in exploring for domestic deposits of strategic materials.	a. Improve the economics of domestic deposits of strategic material resources through tax incentives for exploration and development.	Cost to government arises only if deposits of strategic materials are developed. Costs are limited to tax liability of those deposits.	Tax incentives can only improve project economics by several percentage points. They cannot turn deposits similar to known domestic chromium, cobalt, and manganese deposits into profitable ventures.
	b. Reduce the cost of exploration by increasing level of detail obtained by government resource assessments and by conducting R&D to improve exploration technology.	Could reduce cost of identifying areas of possible deposits and allow industry to conduct more exploration within current exploration budgets.	Actions are not material-specific and are unlikely to result in increases in exploration for strategic resources unless coordinated with other incentives.
	c. Improve ability to predict location of possible deposits of strategic material resources through increased understanding of ore formation processes.	Could lead to location of deposits that cannot be found by current exploration equipment or methods.	Unlikely to result in discovery of any deposits of strategic materials resources until greater scientific understanding is achieved—a process that could take many years.
2. Known domestic strategic material sources are economically noncompetitive, and therefore not currently producing.	Federal subsidies for domestic mining.	Assure domestic supply. Reduce likelihood of disruption occurrence.	High costs relative to purchasing for stockpile on world markets. No guarantee that production period would coincide with any supply disruption.
	a. Cobalt	Could provide an assured domestic supply of up to 10 million pounds per year over 10 to 15 years.	At 1983-84 metal prices, a substantial Federal subsidy would be needed so that it would be cheaper to buy cobalt on world markets for the National Defense Stockpile.
	b. PGM	A relatively small subsidy could assure near-term production of 6 to 10 percent of U.S. needs.	Government action probably not necessary. Market forces alone are expected to promote domestic production — possibly in the next 5 years.
	c. Chromium and manganese	Subsidy would assure production of Cr and Mn in limited amounts over relatively short time period; might encourage domestic exploration activities.	Uneconomic nature of known deposits would require high subsidies: for Cr, two or more times and Mn, seven times market world prices.
3. Magnitude of production/resources of existing concentrated foreign suppliers inhibit development of alternate sources.	Use government resources to expand foreign production of strategic materials.	Reduces likelihood of successful supply disruptions.	Perpetuates reliance on foreign sources. If actions are not targeted, option could promote competition for nonstrategic domestic mining industry.
	a. Improve information about possible projects.	Relatively inexpensive use of resources.	Results tend to be limited and difficult to foresee.
	b. Reduce political risks to U.S. private sector investment.	Relatively inexpensive use of resources.	Targeting to specific minerals is difficult. Results are limited in weak mineral markets.
	c. International direct/indirect aid to encourage foreign projects.	While relatively expensive, many foreign mining projects are marginally economic and could be less costly than domestic subsidies. Aid can be coupled with other developing country needs.	As with domestic subsidies, it would be less expensive at current prices to purchase from existing sources for stockpile.

Table 8-7.—Policy Alternatives for Exploration, Mineral Production, and Processing (Continued)

		Arguments for/against	
Problem	Option	Positive	Negative
4. Declining domestic ferroalloy ore processing capability.	a. Government subsidies to maintain/develop capacity along with ore sources.	Assures processing capability in time of emergency need.	Creates excess global supply.
	b. Government support for modernization efforts and R&D in emerging technologies.	Improves productivity and therefore competitive position of domestic industry. Could target development of flexible production capacity.	Closure of some remaining facilities continues with job loss in near term.

SOURCE: Office of Technology Assessment.

for other minerals, such as copper, lead, zinc, or bauxite, for which there is a substantial record of success to hearten investors.

The Federal Government generally participates in only the first of the four stages of prospecting and exploration, that of wide-scale reconnaissance (table 5-2, ch. 5). Information obtained at this stage helps prospectors select areas for more detailed survey but is unlikely to locate signs of a specific deposit. In view of the prevailing industry belief that commercially competitive deposits of the first-tier strategic materials are unlikely to be discovered, an increase in general information would probably be insufficient in and of itself to encourage more intensive exploration for these specific materials, although such information may indeed encourage exploration for other metals.

To increase the potential for discovery of domestic deposits of first-tier materials, the potential profitability of deposits must increase, the cost of exploration must decrease, or the likelihood of success of exploration must increase. Further, in order to be efficient in the use of Federal resources, actions directed toward these goals should be material-specific. Table 8-7, issue 1, identifies three approaches which could be taken.

The first possibility, increase of profitability of potential deposits, could be approached through tax policy (e.g., increasing the percentage depletion allowance for specified materials), through exploration loans that have reduced rates or reduced principal when they lead to the discovery of deposits that eventually lead to commercial exploitation, and through mining and metallurgy R&D directed specifically at reducing the cost of exploiting deposits for the first-tier materials as they are likely to be found in the United States.

The second approach would be for the Federal Government to undertake, either directly or through contract with private firms, more detailed prospecting activities, again directed at specific types of mineral deposits. This approach could also include the development of improved exploration equipment and techniques, such as the development of geophysical techniques for locating sedimentary manganese deposits, more portable and accurate equipment for geochemical analysis, and lower cost core-drilling equipment.

The third approach, increasing the likelihood of success of exploration, could combine current data collection and analysis procedures with intensified research into the processes of formation of deposits of strategic materials, with the goal of improving the ability to identify areas most likely to have deposits of specific first-tier strategic materials. Predictive geology, based on theories of the formation of mineral deposits, is in its infancy and certainly a long-term approach to strategic materials supply issues.

Domestic Production of Strategic Materials

As discussed in chapter 5, known domestic deposits of first-tier strategic materials cannot support profitable minerals production at current prices. Nonetheless, domestic production could make a contribution to domestic material supplies. Of the materials under study, potential contributions to material supplies (as a portion of U.S. requirements) varies from moderate to large in the case of PGMs and cobalt to small, in the case of chromium and manganese.

Several potentially exploitable PGM deposits exist, the largest of which are located in the Stillwater Complex in Montana. Commercial production of PGMs from one site in the Complex is now under evaluation by a private firm. Other than monitoring progress at the Stillwater site, there appears to be no pressing need for government involvement in this project at this time. It has been estimated that, if a decision to go ahead is reached, about 2 years lead time would be necessary before the mine would produce PGMs. At current prices, domestic production of the other first-tier materials would require a Federal subsidy.

The Federal Government can subsidize—and sometimes has subsidized—domestic production of strategic materials. During World War II and the Korean war, the United States was able to obtain some of its chromium, manganese, and cobalt supplies through heavy subsidization of production from limited domestic deposits. Between 1948 and 1962, about 14 million pounds of cobalt were produced domestically under Federal subsidy.[17] When Federal contracts expired, most domestic production ceased.[18]

Recent concern about strategic materials has rekindled interest in domestic production subsidies through Title III of the Defense Production Act (table 8-7, issue 2). Title III provides several instruments (loans, loan guarantees, guaranteed prices, or purchase commitments) that could be used to support industrial processing and production of strategic materials.

Possible subsidization of domestic cobalt production was among an initial list of Administration projects proposed for possible Title III assistance during congressional debate about reauthorization of DPA for fiscal years 1985 and 1986. In hearings about this legislation, the U.S. General Accounting Office expressed concern that the Administration had not undertaken adequate cost/benefit comparisons among candidate Title III projects for which it sought funding. In April 1984, Congress amended DPA to authorize a total of $100 million in financial aid to defense industrial projects for fiscal years 1985 and 1986.[19] The amendment did not preclude a Title III cobalt project. However, it did establish new procedures for the Administration to follow in seeking Title III authorization. Except in times of a national emergency, Title III projects must be presidentially cleared, and a determination made that the alternative is the most practical means for meeting a shortfall.

It is not clear whether the Administration has any plans to initiate a cobalt project, but the issue of domestic production of strategic materials is likely to continue to be debated in the future.

Potentially exploitable cobalt deposits in the United States include the Blackbird Mine in Idaho, the Madison Mine in Missouri, the Gasquet Mountain Project in California, and the Duluth Gabbro Complex in Minnesota. For domestic production to occur without subsidy, cobalt market prices, about $6 per pound in 1983 and $11 to $12 in mid-1984, would need to rise appreciably and be sustained for a protracted period in order for mine owners to assume the risks of production. Each of these sites has received some scrutiny for possible subsidy under the Defense Production Act. Although DPA can be used to secure materials for the stockpile, it has generally been used to support industrial processing capabilities considered essential for national defense. One proposed method of subsidy has been a "contingent purchase contract" between the government and mine owner. In such contracts, a negotiated "floor price" would be set with the company. The government would be obligated to buy the cobalt only if the company were unable to sell it on the open market.

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[17] James C. Burrows, *Cobalt: An Industry Analysis*, a Charles Rivers Associates Research Study (Lexington, MA: Heath Lexington Books, 1971), p. 111.

[18] Some cobalt continued to be produced at Pennsylvania's Cornwall Mine until 1971 as a byproduct of iron ore production without subsidy.

[19] Public Law 98-265, the Defense Production Amendments Act of 1984, was signed into law by President Reagan on Apr. 17, 1984.

Some evaluation of production economics from candidate sites has been conducted by the sponsoring companies, with estimates ranging from $16 to $25 per pound. However, some of the estimates have not been revised since 1981, and none should be considered definitive. According to the Department of Defense, "contradictory data being quoted and evaluated" led the Air Force, in 1983, to seek "definitive data through legal contracting procedure for a cost/benefit analysis of domestic cobalt production."[20] The form of the Air Force effort, a draft request for proposal,[21] evoked controversy because some believed that a final determination had been made to go ahead with a pilot plant project to evaluate the quality of domestically produced cobalt for defense applications. The effort did not reach the stage in which such definitive data was submitted, however.

The Blackbird Mine (an inactive mine which produced cobalt under DPA subsidy in prior years) is considered the largest potential domestic source. In 1981, the company which owns the mine estimated that Blackbird could support an annual production level of 3.7 million pounds (1,850 short tons) of cobalt for a 14-year period if cobalt prices rose and were sustained at a $20 per pound level or if the government subsidized production.[22] Lead time for production would be 3 to 4 years. A spokesman for the company recently told OTA that it now estimates a sustained cobalt price of $16 per pound to be sufficient to bring the mine into production, owing to discovery of higher grade cobalt at the site, and improved mine planning. It has also increased its mine life estimate to 20 years.

Another inactive mine, the Madison Mine in Missouri, could also support production of cobalt as a primary ore, according to its proponents. Closed since 1961, Madison produced lead, copper, and nickel, and during the 1950s, cobalt under a DPA subsidy. Madison's owner estimates that the mine could produce 2 million pounds of cobalt annually over an estimated mine life of 20 years. In addition, substantial amounts of cobalt are present in mine tailings that have accumulated over the years from lead and zinc mining in the area. These tailings could provide 300,000 to 500,000 pounds of cobalt annually, using prevailing lead and zinc recovery technologies, but far more if other processes were adopted. The Madison mine owner estimated in 1981 that a cobalt price of $25 per pound would be necessary to bring the mine into production. Revised estimates apparently have not been made since then.

The Gasquet Mountain Project, a proposed mine on National Forest land in California, would involve production of cobalt and some chromite as coproducts of nickel production. A 1981 feasibility study for the project estimated that the lateritic deposits at the site could support annual production of 19.4 million pounds of nickel, 2 million pounds of cobalt, and 50,000 tons of chromite over an estimated mine life of 18 years. The economic feasibility of the project would thus depend on multiple metals prices, with changes in the relative value of one metal, compared to the others, affecting production economics. For example, if nickel prices were $3.50 per pound, cobalt production would be viable at $12.50 per pound. If nickel prices rose to $3.96 per pound, cobalt would be viable at $8 per pound, but if nickel prices were $2.21 per pound, a cobalt price of $25 would be required.[23] Nickel prices in 1983 were $2.20 per pound. A company spokesman told OTA that it had not revised its economic evaluation since 1981.

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[20] Department of Defense submittal entitled "General DoD Comments on the Classifed GAO Statement," in U.S. Senate Committee on Banking, Housing, and Urban Affairs, *Reextension of the Defense Production Act*, hearing held Sept. 15, 1983, (Washington, DC: U.S. Government Printing Office, 1983), p. 161.

[21] Department of the Air Force, Draft Request for Proposal (DFRP) for Contemplated RFP F33615-83-R-5106: Establishment of Domestic Cobalt Production, Aug. 30, 1983.

[22] Letter of R.V. Fiorini, Vice-President, General Manager, Noranda Mining Inc. to Senator Harrison S. Schmidt as reproduced in U.S. Senate Committee on Banking, Housing, and Urban Affairs, Defense Production Act and the Domestic Production of Cobalt Hearing, Oct. 26, 1981, Senate Hearing 97-38 (Washington, DC: U.S. Government Printing Office) p. 143.

[23] Documents provided to OTA on the Gasquet Mountain Strategic Metals Project by the California Nickel Corp. in March 1983. The figures cited above assume a constant chromite price of $40 per ton.

In assessing the desirability of subsidizing domestic cobalt or any other strategic material, several considerations should be kept in mind. Supply security is the primary argument used in support of government assistance for domestic cobalt production. To some, the risks entailed in continuing to depend on insecure foreign sources of cobalt is an overwhelming argument in favor of a domestic production subsidy even when cobalt could be more cheaply acquired from world markets for the stockpile. The supply security aspect of domestic production is most persuasive if the risk that a protracted supply disruption will occur before adequate quantities of cobalt could be acquired for the stockpile is seen as unacceptable. To those who think the short-term risks of a supply disruption are not great, stockpiling now, rather than depleting limited domestic cobalt reserves, seems to provide greater supply security in the long term.

Fluctuating cobalt or coproduct metal prices have made it difficult to identify the extent of subsidy that would be needed, compared to simply buying cobalt on the world markets for the National Defense Stockpile. If 1980 cobalt prices ($25 per pound) were to return and be sustained, domestic production of cobalt would compare favorably with world prices, and thus could be cost effective even with minimal government involvement. At 1983 cobalt prices, about $6 per pound, it would cost the government three to four times as much to buy cobalt from domestic mines than from the world market. If it is assumed that mid-1984 cobalt prices (about $12 a pound) will continue, stockpiling from world markets would still be cheaper than subsidizing domestic production.

Environmental considerations may also delay or potentially curtail proposed projects, especially when supply security objectives are not widely perceived as a pressing need. Concerns about possible water pollution and environmental damage to California's Gasquet Mountain were raised in the legislative debate about the 1984 DPA amendments.[24] The Blackbird Mine is surrounded by Federal lands, including 40,000 acres which has been classified as wilderness with a stipulation that it will remain open for cobalt exploration and mining activities. Although open, actual development of the mine could be delayed by the proceess of establishing Federal regulations governing access to the site across Federal lands. Water pollution problems arising from the presence of arsenic will have to be overcome before production can begin.

Encouraging Foreign Production of Strategic Materials

The United States is likely to be dependent on a few producing countries for most of its supplies of strategic materials for the foreseeable future. Actions can be taken to increase the number of countries supplying these materials, thus achieving greater diversity of supplies. However, these actions take time to implement and are not likely to alter fundamentally the supply patterns in the next decade. Over the long term, a concerted effort to promote diversity of foreign supply sources of specific minerals could help reduce overall U.S. vulnerability to a supply disruption. To be most effective, these actions must be narrowly focused to address problems that are mineral-specific and to avoid possible competition with efforts to develop domestic sources.

Potential benefits of supply diversification strategies will vary by material. Of the first-tier materials, for instance, prospects for supply diversification appear to be best for manganese, which already has the most diverse supply. Several alternative supply sources also exist for chromium, such as expanding output in Turkey and the Philippines. Cobalt diversification, primarily in the Southwest Pacific, depends to a large degree on world markets for nickel and copper, since cobalt is usually a byproduct of production of these metals. In the case of PGMs, the most promising known but nonproducing deposit is in the United States. Outside the United States prospects for PGM supply diversification will depend on new discoveries rather than on the development of known deposits.

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[24] Environmental concerns associated with Gasquet Mountain were discussed in House debate on the conference report on the DPA amendments. (*Congressional Record*, H2538, Apr. 17, 1984.)

The likelihood that a supply diversification strategy will succeed also depends in part on the extent to which the Federal Government and U.S. industry are willing to accept the risks and attendant costs associated with bringing alternative supply sources on line. According to a 1982 GAO report, direct investment by U.S. firms in mining and smelting activities in developing countries has fallen significantly since the late 1960s and early 1970s.[25] Reasons for this include prolonged weak markets, perceived risks associated with such investments (due to political uncertainties), and controls on investment asserted by producer countries. On the other hand, the involvement of multinational mining firms in developing countries is still extensive. While equity participation has declined, firms are willingly supplying technology and management services.

New mining ventures from exploration to production can cost $1 billion and more. Moreover, mining prospects are long-term ventures. Exploration activities to discover new deposits can take many years and are often unsuccessful. Once a deposit is identified and found to be promising, a minimum of 2 to 5 years is required to bring a new mine into production; somewhat less time is required to increase output from an existing alternative mine that is already in operation. Hence, actions taken to promote diversity of supplies must be planned and executed far in advance and are not likely to be successful as a way to avert immediately the consequences of a supply disruption. Even if financial obstacles were overcome, supply diversification strategies have inherent risks. Near the end of World War II, and through much of the 1950s, the Federal Government supported development of Cuban nickel resources to diversify U.S. supplies. The effort was successful in developing Cuban nickel, but for political reasons the United States has not had access to this supply since the early days of the Castro regime.

In some countries the government plays a very active role in backing international resource projects launched by private firms. In Japan, for instance, overseas ventures of sufficient importance to be considered "national projects" are backed by low-interest loans to both the country in which the project is located and the consortium of Japanese firms involved in the project. The government itself serves as the major stockholder in the consortium. Among industrialized nations, Japan is unusual in that half or more of its foreign mining and smelting investments are in developing countries—as compared to 25 percent among U.S. firms.[26]

In the United States, private industry—not government—plays the primary role in securing mineral supplies from foreign sources, and this policy is likely to continue. However, the Federal Government can be a catalyst in promoting private investment overseas, through the dissemination of essential information, by facilitating interaction between private industry and foreign owners, and by the targeting of international aid to private and producer country mining activities that are related to strategic materials. The extent and degree of encouragement considered appropriate can range from modest to extensive, depending on the importance given to supply diversification in overall U.S. strategies to reduce import dependency.

The Reagan Administration has emphasized information development to encourage private action. Initiatives include a Department of Interior minerals training program for State Department regional resource officers to improve the collection of information. It also includes discussions with market economy countries about mineral investment problems and the need for more consistent statistical reporting. In fiscal year 1983, the U.S. Geological Survey (USGS), in cooperation with Canada, West Germany, Australia, South Africa, and Great Britain, began an International Strategic Mineral Inventory program to upgrade and standardize resource and production information about world deposits of chromium, nickel, manganese, and phosphate. Other minerals are expected to be added to the inventory. The USGS Office of International Geology obtains funding through the Agency for International Development (AID) for various mineral potential studies of developing nations. These projects are often cooperatively funded by the developing nation, must be "sold" to AID on the basis of their assistance to immediate development needs, and do not necessarily focus on strategic materials. (Phosphate for agricultural purposes is a major item.)

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[25] U.S. General Accounting Office, *Federal Encouragement of Mining Investment in Developing Countries for Strategic and Critical Minerals Has Only Been Marginally Effective* (Washington, DC: U.S. General Accounting Office, 1982).

[26] Ibid., p. 5.

President Reagan has also given new responsibilities to the Trade and Development Program (TDP) of the International Development Cooperation Agency (IDCA) in order to "broaden opportunities for the U.S. private sector to participate in the development of and diversification of foreign sources of supply of strategic materials."[27] The mineral resources group of TDP received funding of about $700,000 in fiscal year 1984 which is supplemented by cooperative funding for specific projects. TDP concentrates its efforts on a small number of strategic minerals and, as of March 1984, had issued five reports that identified investment possibilities in those minerals for U.S. mining companies in foreign countries.[28] TDP also brings private project promoters and prospective investors together informally to discuss foreign mining and processing projects. The TDP reports have been thoroughly prepared and are potentially useful; however, some industry people claim they provide information already available and that the analysis is not extensive enough to attract private investment, especially during periods of depressed minerals markets.

One TDP report has resulted in a TDP followup contract for a feasibility study to further encourage private industry's involvement. Future reports might be more useful if they included possible followup steps for government action to be considered by relevant agencies (e.g., technical or financial assistance), and joint venture opportunities for the private sector. Although TDP's approach is promising, funding levels may be too low to realize any substantial improvement in diversified minerals sources.

Other Administration efforts have involved the development of a model bilateral investment treaty. When adopted by individual countries, such a treaty may improve a country's investment climate, but does not necessarily create mineral investment opportunities.

An alternative or complementary approach would be to target or give special priority to strategic materials in U.S. bilateral assistance programs, or as part of U.S. responses to multilateral assistance in which it participates (table 8-7, issue 3). The 1980 National Materials and Minerals Policy, Research and Development Act emphasized the importance of such activities by calling on the President to "assess the opportunities for the United States to promote cooperative multilateral and bilateral agreements for materials development in foreign nations for the purpose of increasing the reliability of mineral supplies to the Nations."[29] Major multilateral and bilateral programs applicable to mineral development are highlighted in box 8-A.

Multilateral programs, established by the United Nations, the World Bank group, and other international organizations, have been the primary means (albeit indirect) for U.S. assistance for mining and smelting activities in developing countries. These programs, according to the GAO report, have had a limited impact on increasing supplies of strategic materials of importance to the United States. Of 45 mineral-related projects during 1971-80, most involved copper, lead, zinc, and iron ore,

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[27] *National Materials and Minerals Program Plan and Report to Congress*, op. cit., p. 11.

[28] Reports cover manganese in Mexico, cobalt in Morocco and Peru, and chromium in Turkey and the Philippines.

[29] Sec. 4(9) of Public Law 96-479.

Box 8-A—Bilateral and Multilateral Assistance Approaches for Mining Investment in Other Countries

Bilateral Approaches:

- *Overseas Private Investment Corporation (OPIC)* was established in 1969 to facilitate flow of private U.S. capital and skills to the Third World through insurance, financial guarantee, direct loan, and promotional programs. Mining and energy initiatives were instituted in 1977 to help revive investor interest in developing country mining projects. Although OPIC does not support a significantly large number of projects, the mining projects that it does support are generally targeted to strategic minerals.
- *Export-Import Bank* was created in 1934 to provide financial support for U.S. export sales through direct loans, financial guarantees to private lenders, and commercial and political risk insurance. Unlike most assistance programs, Ex-Im operations are not limited to developing countries. Programs were directed toward specific mineral needs during World War II and the Korean war using the Reconstruction Finance Corporation and the Defense Production Act as sources of funding. Since then, however, lending (for mining equipment exports) has been limited and has not focused on strategic minerals. The Bank has no control over the mix of incoming applications it processes. Weak markets and inability to compete effectively with foreign counterparts have resulted in only a few mineral projects.

Multilateral Approaches:

- *Development Banks* (e.g., the World Bank, Asian Development Bank, and Inter-American Development Bank) tend to devote small shares of their overall funding to mineral projects and have no mechanism to target "U.S." strategic materials when the strategic materials of other involved nations are different. Priorities for addressing basic needs of people limit mineral projects to those which are viewed as a way to improve foreign exchange earnings and balance of payments postures. Development bank activities sometimes conflict with U.S. domestic mining interests by promoting the development of foreign competition.
- *U.N. Revolving Fund for Natural Resources Exploration* was set up in 1973 to help increase natural resources exploration in developing countries and expand the world's known resources base. Its mission is to address what experts perceive to be the greatest mining-related problem for developing countries: insufficient exploration. While exploration costs generally are not great compared with mine development costs, the risks are greater due to a lower probability of success. Therefore, funding is difficult to obtain—even from development banks. The Fund, which contracts actual work to the private sector, deals in exploration projects exclusively although it does have the authority to do follow-up feasibility studies. Of 11 projects completed in 1983 and 5 continuing on through 1984, none involved first-tier strategic materials. According to GAO, by 1982 the Fund had not yet demonstrated its capabilities convincingly, having had financial and initial problems in convincing governments to use its services, and in obtaining contributions to set up the fund.
- *International insurance plans* to safeguard foreign investment have been proposed but never implemented, due to lack of agreement on how to arbitrate disputes, negotiate claims, finance the plans, or distribute voting rights. Recent proposals and sponsors include: International Investment Insurance Agency (1966), World Bank; International Resources Bank (1975), U.S. Government; Inter-American Fund for Energy and Minerals (1979), Inter-American Development Bank.

and only four involved strategic materials. Multilateral programs that support exploration activities, such as the U.N. Revolving Fund for Natural Resources Exploration, have some potential to result in new discoveries of strategic materials.

Several bilateral aid programs could be specifically targeted to encourage U.S. firms to invest in mining activities for strategic materials. Past efforts have been only marginally successful, as was brought out by the GAO report. Among other things, the report found that existing programs were not oriented toward providing solutions to what are, after all, mineral-specific problems (the TDP studies, a notable exception, were only beginning at the time of the GAO study) and that there was a lack of coherent investment strategies to guide implementation actions over the long term.

One of the often stated impediments to mining firm investment abroad is the fear of political instability. A mining firm will launch a project only if it believes that the project will yield an adequate after-tax return on equity over a specified time period. Political risk insurance can reduce the political component of economic decisionmaking. The Overseas Private Investment Corporation (OPIC), established by Congress in 1969, provides such insurance as well as financing (loans and loan guarantees) to U.S. firms investing in developing countries. Its involvement in mineral projects, however, has been limited due to the weakness of markets and, in the area of natural resources, it concentrates on energy projects. OPIC, like the Export-Import Bank (see box 8-A), assists rather than subsidizes foreign projects. Thus, it can improve the competitive posture of U.S. firms but not the markets wherein firms must operate.

GAO cited policy and procedural restraints on OPIC's activities as limiting factors on the number and type of mineral projects it supports. As a public corporation, OPIC must assure that, overall, its investments generate a positive return. To do so, its investments are broadly based in terms of industries and countries served. Loans granted by OPIC are restricted by legislation to small businesses, which disqualifies the majority of mining firms. Loan guarantees (up to $50 million) are available only for the production phase of mining projects. OPIC political risk insurance maximum ($125 million) may not be consistent with the real costs of most mineral investment activities today, although it does provide 20-year coverage of the entire mineral exploitation process from exploration through production.

The President's materials plan does not address foreign aid or loans as an instrument of national minerals policy. When more limited means do not encourage the diversification of sources, it may—given the perception of risk—be appropriate for the Federal Government to engage in direct financing support for exploitation of, or creation of demand for, these diversified sources. Stockpile needs and other Federal Government purchases, for example, could be directed at creating demand for unexploited strategic materials deposits. Loans and loan guarantees could assist countries both directly and indirectly in exploiting mineral resources. For instance, prospective mining projects are often located inland, without adequate in-place transportation and energy infrastructure. Developmental aid for such supporting projects could overcome economic obstacles to mine development, provide investment opportunities for U.S. firms, and, at the same time, stimulate the overall economic growth of a developing nation.

In using both multilateral and bilateral mechanisms, a clear distinction must be made between the needs of the domestic mining industry and those of U.S. firms involved in the international mining industry. Policies developed for one may be viewed as detrimental by the other. The domestic mining industry today faces increasing competitive pressure from foreign mining that is supported by governments that are more concerned with generating foreign exchange or jobs than with profits. Many of these ventures may be supported either directly or indirectly by public sector international development banks. The domestic industry, which is guided by the principles of the free market, says it cannot continue to compete in global markets under these newly emerging and unfamiliar rules of competition. Conversely, U.S. firms involved in foreign mining projects can take advantage of them. Clearly, for commodities where domestic mining competes with foreign mining, a policy choice must be made that serves both sectors or just one. Fortunately, inherent in the nature of "strategic materials" is the fact that little, if any, domestic mining occurs for these commodities at present. If policies are specifically targeted, they would have less chance of being detrimental to the domestic mining industry and greater likelihood of success in diversifying U.S. supply sources.

Implications of Diversification of Supply for Ferroalloy Production

Diversification of ore suppliers offers only a partial solution for decreasing the potential for interruption of supplies of chromium and manganese. Since the bulk of chromium and manganese ore is processed into ferroalloys for use in the production of steel, stainless steel, and superalloys, it is also necessary to ensure that ferroalloy production facilities will be available to process ore obtained from a variety of suppliers.

The domestic ferroalloy industry was once the major supplier of ferroalloys to the U.S. steel industry, but this position has been eroded by foreign suppliers such as South Africa, France, and Brazil. This decline can be attributed largely to nontechnical factors, particularly:

- policies by foreign governments and international organizations that provide financial incentives that encourage development and operation of ferroalloy production in developing countries, primarily in conjunction with operating mines;
- higher cost for U.S. labor in comparison to labor costs in other producing countries;
- current exchange rates that, due to the strong U.S. dollar, favor the use of imported products over domestic production; and
- higher capital investment required of domestic producers in order to meet stringent U.S. environmental and safety requirements.

The domestic ferroalloy industry has a number of strengths, including large, in-place capacity for production of ferroalloys; adaptability of furnaces between various manganese, chromium, and silicon products (although conversion between products is, in some cases, limited by design of electrical or pollution control systems) and proximity to markets for ferroalloy products that allows quick response to special orders for nonstandard products.

One way to assure ferroalloy processing availability would be to encourage the construction of processing capacity along with chromium and manganese mines, but this method would provide excess worldwide capacity and be wasteful of capital investment. A second alternative is to maintain a ferroalloy processing capability in the United States, one designed to be flexible both in products (ferrochromium, ferromanganese, silicon, and ferrosilicon, and specialty products such as calcium silicon) and in production rates (with plants designed for rapid expansion of capacity).

New technology may change the outlook for the domestic ferroalloy industry in two ways. First, process improvements, such as increased use of automated equipment and computer control, may increase labor productivity, reduce energy consumption, and raise the quality of products. These improvements, in turn, would improve U.S. competitiveness, since high labor and energy costs are a contributor to the high cost of domestic production, and the quality of products for specialty steels and superalloys can protect and strengthen the U.S. position in these markets. The second major technical change facing the industry is the adoption of plasma arc and high-voltage electric furnaces. These advanced furnaces, which are in the latter stages of development and the first stages of commercial use, may offer lower operating costs and improved energy efficiency over the submerged arc furnaces now in use. However, they must be built to replace furnaces now in use, which will require the industry to make major capital investments. These new furnaces are applicable both to domestic and to foreign production, so it is possible that the domestic industry could be left behind its foreign competition if it is slow to adopt the new processes.

Since the immediate problems of the ferroalloy industry arise from political and economic factors rather than technical ones, the principal response of the government (if it is to respond) is likely to be political. In the longer term, however, there are more options (table 8-7, issue 4). First, the Bureau of Mines can work with industry to develop process improvements, particularly in the area of automation and computer control, that increase labor productivity and reduce energy and material consumption. Second, financial incentives, such as increased depreciation, tax credits, or low-interest government loans could be used to encourage the adoption of new ferroalloy furnaces. Third, the government could use its influence in international lending organizations to encourage the use of development loans for projects other than ferroalloy facilities. Fourth, additional support, either as loans or grants, could be provided to the ferroalloy industry to include in plant designs the potential to increase capacity or shift between products rapidly when supplies of imported ferroalloys are unavailable and ores must be processed for domestic industries.

Substitution and Advanced Materials

In discussing substitution, it is useful to differentiate between two broad classes of alternative materials: *direct substitutes*, i.e., materials that, while not necessarily preferred, could replace materials now in use; and *advanced materials*, which may displace currently used materials in time because the new material offers a clear advantage in performance, cost, or other benefit. In contrast to direct substitutes, which may require only minor design changes for use, advanced materials often require redesign of products for optimal use.

Direct substitutes are immediately available for many applications that now use first-tier strategic materials. However, this is not the case for some applications that are most critical to the national defense and the U.S. economy. As discussed in chapter 7, the Federal Government sponsors considerable R&D aimed at finding direct substitutes for strategic materials. Much of the research has focused on development of lower chromium alloys as potential replacements for stainless steels of high-chromium content, and on alternative jet engine superalloys which contain reduced amounts of cobalt or other strategic materials. This research adds to the choices of materials available to designers. However, institutional and economic barriers impede acceptance of these materials so that many will not be fully developed. Substitutes used in highly demanding applications need to undergo extensive testing and qualification before they can be used. Industry has little incentive to undertake this testing unless the substitute offers a clear advantage over currently used materials.

Besides direct substitutes for materials now used, the Federal Government also plays a primary role in sponsoring research on advanced materials, such as advanced ceramics and composites, and rapidly solidified metals. These materials have long-term promise to change current requirements for strategic materials—although to what extent is difficult to predict due to the need for redesign of product components. In some applications, net savings in strategic materials may occur, while in other applications, product redesign could lead to increased use of strategic materials.

Many barriers must be overcome before use of these advanced materials becomes widespread. Some barriers are technical, arising from the materials themselves or from the need to improve current processing techniques so that reliability is increased. Others are institutional and economic. Some of these materials are much more expensive than currently used materials, although costs may go down in time as processing problems are overcome. From the institutional side, widespread use of these materials may have to await establishment of standards and specifications for their use, as well as greater emphasis on these materials in engineering curricula.

An emerging import vulnerability issue concerns adequacy of domestic processing and manufacturing capabilities for advanced materials. Most advanced materials are made from raw materials which are plentiful in this country. However, the manufacturing capabilities (including technology and technical know-how) to produce qualified materials suitable for the most demanding applications is distributed among several nations. Most advanced materials are in limited production status at this time. As they become more frequently used, the extent to which the United States should attempt to become self-sufficient in all stages of production of these materials is likely to be increasingly debated.[30]

Table 8-8 shows selected policy alternatives with respect to substitution and advanced materials. Although some policy issues associated with direct substitutes and advanced materials are held in common, there is enough divergence to merit separate discussion, as is done below.

Direct Substitution Options

The Federal Government is the primary sponsor of R&D on direct substitutes for strategic materials. Except in times of a supply shortage, industry has little incentive to conduct such activities unless the substitutes afford a clear benefit of cost or performance.

Emphasis on substitution research among Federal agencies has accelerated since the mid-1970s. Several Federal agencies, including various defense agencies, NASA, the Bureau of Mines, and the DOE national laboratories undertake or sponsor strategic materials substitution research. Despite recent budget cutbacks, Federal funds available for substitution research appear to be quite healthy, with some gains and losses among different Federal agencies. The Bureau of Mines substitution research effort has increased recently, while NASA's Conservation of Strategic Aerospace Materials (COSAM) program has been cut somewhat. The COSAM program has resulted in some superalloys with reduced cobalt content that have the potential to directly replace existing superalloys. These materials have not received extensive development beyond the laboratory stage. A more fundamental purpose of the COSAM program was to sponsor *basic* research that would shed light on the function that strategic materials play in superalloys. (Table 8-5 shows total U.S. expenditures for substitution on specific strategic materials for fiscal year 1980, the last year in which governmentwide data is available.)

Federal sponsorship of substitution research is generally conceded to be essential if research programs are to be undertaken on a sustained basis to find direct substitutes for strategic materials. However, this research alone will not do much to reduce overall vulnerability unless promising substitutes are developed to the point that they can be used by industry. The time lag between initial laboratory development of an alternative material and the stage in which it is ready to be used is often protracted; many expensive and time-consuming intermediary steps must be surmounted before the material can be considered "on the shelf." The extent to which the Federal Government needs to be involved in narrowing this gap depends on the relative weight that is given to substitution in an overall strategy to reduce import vulnerability.

Actions the Federal Government could take, besides its continuing important role as the primary sponsor of research on substitutes, are identified in table 8-8 and discussed below.

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[30] For a discussion of initial self-sufficiency issues associated with the advanced composites industry, see Stanley L. Chamon, *Industrial Base and Qualification of Composite Materials and Structures (An Executive Overview)* (Arlington, VA: Institute for Defense Analyses, 1984). Concern about U.S. reliance on foreign sources and a sole domestic supplier for polyacrylonitrile (PAN), used in production of some carbon composites, was one issue discussed in the legislative debate about reauthorization of the Defense Production Act in 1984.

Table 8-8.—Policy Alternatives for Substitution and Advanced Materials

		Arguments for/against	
Problem/issue	Option	Positive	Negative
Direct substitution:			
1. Information about available substitutes which would entail less use of strategic materials may be difficult for small firms to obtain, hence delaying their ability to respond to a supply disruption and possibly impeding initiative to ease import dependency in advance of supply difficulties.	Sponsor a substitution information program to disseminate information to industry, giving private sector (testing societies, trade associations, universities, and industry) key roles in designing and implementing the program so that it is of maximum utility to end users. Option appears most promising as a means to reduce chromium overspecification in stainless steel.	Would enhance U.S. substitution readiness—especially in the case of chromium, for which major opportunities to conserve chromium in nonessential application exists; would provide "continuing visibility" for strategic material concerns by setting up an institutional program to disseminate information.	Information could become obsolete quickly; industrial users may not have as great a problem in obtaining such information as is sometimes contended (i.e., industry would have a great incentive to find this information in the event of a supply difficulty).
2. Work on promising laboratory substitutes that could reduce strategic material requirements is often ended at an early stage because of lack of industry incentives to develop these materials on their own, and because Federal agency research funds may not be provided for the long period of time needed to develop substitutes fully for commercial use.	Sponsor a joint government-industry effort to develop selected promising substitutes to the point where they can be commercially used, focusing on lower chromium alloys that could reduce chromium requirements for stainless steel.	Could result in long-term reduction in import vulnerability if substitutes were successfully developed so that they could be used by industry; Federal sponsorship of applied research to develop direct substitutes may not be justified unless more substitutes are developed to the point where they could be commercially used.	Long-term nature of commitment, plus the expense of developing particular alloy substitutes may mean that other options (e.g., diversification of supplies and recycling) would be more useful. Government has limited experience with alloy development and should leave development to industry alone.
Advanced materials:			
3. Problems in coordinating advanced materials R&D at the executive branch level have long been apparent. The new National Federal program for advanced materials R&D, established by the National Critical Materials Act of 1984 (Public Law 98-373) is intended to overcome this difficulty. The flexibility given to the executive branch in formulating this program, could lead to innovative approaches, but a danger also exists that congressional intent will be misconstrued.	Exercise oversight functions on the Administration's Federal program plan for advanced materials R&D, to establish early and continuing guidance to the National Critical Materials Council and other implementing agencies about program direction, goals, and specific initiatives.	Would help the administration establish goals for Federal activities with respect to advanced materials; would give greater visibility to advanced materials in the executive branch, Congress, and the country as a whole.	Oversight process, if taken to an extreme, could lead to a disproportionate expenditure of EOP staff resources on meeting congressional information demands, which would be contrary to the intent of Public Law 98-373 as expressed in its legislative history.
4. Advanced materials use may be impeded by lack of qualified engineers, designers, and material scientists trained in the use of these materials.	Provide startup education and curriculum development grants to U.S. universities to expand faculty and to stimulate research and graduate/undergraduate programs in advanced material studies and in design with these materials.	May help U.S. maintain competitiveness of its advanced material industries through research and training of personnel needed to establish domestic capabilities.	Industries that stand to benefit from such educational activities should assume primary responsibility for meeting their technology and personnel needs through contributors to educational institutions.
5. Widespread adoption of advanced materials may require development of more uniform testing methods, material specifications, and procedures for certification and qualification than currently exists, as well as an improved and updated data base to facilitate use of advanced materials.	Sponsor initial activities in conjunction with testing societies, industry, and academia and relevant Federal agencies to develop guidelines and data requirements for testing methods, specifications, procedures, and design with advanced materials.	May encourage more widespread use of advanced materials by providing greater certainty to material producers and consumers about conditions in which they can be appropriately used.	Government should not attempt to "force" premature uniformity on a developing technology. Evolution of needed information systems can best be accomplished incrementally by users and suppliers as the need arises.

SOURCE: Office of Technology Assessment.

These actions are of two kinds: greater government involvement in developing the information needed to facilitate industry use of new materials; and greater Federal support for the post-laboratory development of direct substitutes.

Providing Substitution Information to Industry

Many on-the-shelf technologies and materials could lower strategic materials consumption in the United States, and potential substitutes are at various stages of development. These alternative materials and technologies are well known to defense industries, automakers, and other large or technologically advanced industries. However, many small or technically unsophisticated firms ordinarily would not have easy access to information about specific materials, technologies, and applications in which substitution could lessen strategic materials use. Difficulties in obtaining information about alternative materials might lengthen their substitution response time in a supply disruption—a critical concern, especially for firms that are not likely to receive an allocation preference in the event of a supply disruption of major proportions.

The need for a more effective mechanism for collecting and transferring information about strategic materials substitutes to industry and end users has long been recognized by the materials community (table 8-8, issue 1). Several major conferences on materials, as well as various testing societies and industry organizations, have recommended that a substitution information program of one sort or another be an essential component of strategic materials policy.[31] Some steps have been taken by government agencies, trade organizations, and professional organizations to improve substitution information availability, but these have been conducted on an ad hoc basis without a sustained focus.

Information programs of varying scope and complexity have been proposed. At the most basic level, an ongoing program of conferences, seminars, and information dissemination has generally been seen by the materials community as a relatively inexpensive and effective way to heighten industry awareness of research developments relevant to strategic materials substitution and conservation opportunities. Many Federal agencies and private organizations have contributed to such programs in the past, but a continuing program of this sort does not exist.

Others see a need for a national information repository for substitution studies, including studies on alternative materials, analyses of alternative processing techniques, substitution case histories, and directories of experts on particular technologies or material substitutes. Much of this information may be available through individual agencies or through the National Technical Information Service (NTIS), which has been given augmented responsibilities by the Reagan Administration to transfer information about Federal technology development to the private sector. But the demands placed on NTIS may be too diffuse to address effectively the particular issue of strategic materials substitution.

At a more ambitious level, various organizations and individuals have proposed establishment of a "substitution information stockpile" to provide engineers, designers, and procurement officials with highly technical information needed to make decisions about available substitutes. As generally proposed, this "information stockpile" would identify, systematize, and compile detailed information about the properties and potential applications for currently available and qualified alternative materials. Often, systematized information about alternative processing and fabrication technologies that could conserve strategic materials is seen as an essential component of the information stockpile. The primary purpose of such a stockpile would be to reduce response time in a supply disruption. However, it is possible that more firms would adopt their own contingency strategies for reducing their dependency on imported materials if they were aware of available substitution opportunities.

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[31] The importance of substitution information is illustrated in recommendations made at a workshop on conservation and substitution for critical materials held in 1981 at Vanderbilt University under sponsorship by the Departments of Commerce and the Interior. Of 27 recommendations, 10 involved development, compilation, and dissemination of information related to substitution, conservation, and displacement of critical metals.

Even though often proposed, specific steps toward development of an information stockpile have been limited. Part of the reason for this may be that developing a proper format for the information—a technical handbook or computerized data bank that could be available to industry—could be quite difficult. Safeguards, for example, would have to be built into the system to assure that the information, however presented, clearly delineates those applications in which qualification is required from those in which it is not. Another reason may be a concern that a handbook or data bank could quickly become obsolete, presenting stale information of little value. Hence, revision and updating of the information stockpile would be essential. Finally, testing societies and trade associations have limited resources available for such purposes, while the Federal Government has focused most of its substitution effort on research.

Although some components of an information program—conferences and library repository, for example—have broad relevance to strategic materials, the substitution bank concept would probably be of greatest practical use for chromium—especially as used in stainless steel. Designers frequently overspecify (use higher chromium content stainless steels than may be needed) in many noncritical applications. Stainless steel is used in a wide variety of applications throughout the economy; an estimated 60 percent of this demand is for applications in which adequate substitutes are available, or in which some substitutes may be developed after a period of R&D. Ready access to information about these substitutes could help the consumer of chromium for nonessential uses to respond to a supply disruption and ease problems the government might have in allocating available chromium to essential uses.

Initial work on chromium substitution options includes a major report by the National Materials Advisory Board and an industry survey by the Metal Properties Council, which is an active supporter of the substitution bank concept. (This latter effort has been supported in part by NBS.) In this regard, it should be noted that a nonprofit entity, called the National Materials Property Data Network, Inc., has recently been established to explore ways for providing computerized data on engineering materials.[32] Additional work to define the feasibility and parameters of an information stockpile would be needed.

Development of a substitution information program would require extensive interaction between government and the private sector, including participation of testing societies, trade associations, professional societies, and industry. This need for extensive private sector involvement in development and use of the information program may mean that the government's key role would be sponsorship—not actual conduct—of the program. For example, the government could provide funds to a testing society, a university, or other nonprofit organization, to establish a nonprofit center with a specific mission and charter to develop information about substitute materials and new technologies that would help conserve strategic materials. Participation of key Federal agencies, such as national laboratories, NASA, NBS, the Bureau of Mines, and the Department of Defense could be structured into the center's charter.

Developing Substitute Alloys

As a general proposition, the Federal Government's role in developing substitute materials often ends at an early stage of laboratory research. Research results may be published, but it is usually left to private industry to decide whether additional development steps should be taken. Thus, many strategic material substitutes are not placed on the shelf by federally sponsored research, nor are they likely to be fully developed by industry unless the new material is seen as providing significant cost or performance benefits compared to currently used materials.

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[32] See National Materials Advisory Board, *Materials Properties Data Management Approaches to a Critical National Need* (Washington, DC: National Academy Press, 1983), NMAB—405, for a discussion of the need for upgrading U.S. materials properties data bases.

Substitute materials used in critical applications, such as in powerplants and chemical plant processing, must be extensively tested after their initial development in the laboratory. Depending on the application, it can take 5 to 10 years and several million dollars to develop and qualify new materials or processes to the point that they can be used by industry.

Many—perhaps most—of the direct substitutes that have been developed with Federal funds would be more expensive (at current prices) than the materials they would replace. A few are potentially cost competitive with currently used materials and thus might be used by industry if the qualification hurdle were overcome.

Given this situation, the question arises as to what steps, if any, could be taken by the Federal Government to bring potential substitutes closer to commercial use? One alternative would be for government to support a cooperative effort with the private sector to select, fully test, and qualify (where necessary) a few materials with significant potential to reduce critical material needs (table 8-8, issue 2). Most of this effort would probably involve contracts with industry, testing societies, and universities to carry out key roles. Once these materials were fully developed, they would be available for use by industry or could serve as a kind of standby "national emergency alloy system," analogous to the national emergency steel system developed in World War II.

Such a step would not necessarily entail a major new Federal program: it could be accomplished through selective targeting of strategic materials development activities to focus on those materials considered to be most critical to U.S. substitution preparedness. Both the Defense Production Act and the Stockpile Revision Act authorize the President to develop substitutes for strategic and critical materials. Federal agencies, such as the Department of Defense, Bureau of Mines, and NASA, from time to time sponsor test heats and other development activities of substitute materials on a cooperative basis with industry. Moreover, the Federal Government has sometimes sponsored new materials for qualification by testing societies. Oak Ridge National Laboratory is now sponsoring a 9 percent chromium steel for use in powerplants, for example,[33] and the Department of Defense has played a key role in the commercialization of many materials considered essential for defense purposes.

Obviously, because many substitutes are potential candidates for augmented development activities, considerable care would be needed in selecting the materials. Selection of any materials for further development work would depend on many considerations, including their technical prospects, degree of industry interest, and potential contribution to reducing import vulnerability relative to other strategies (e.g., stockpiling or recycling).

For example, as discussed in detail in chapter 7, several superalloys with reduced cobalt content, intended as direct replacements for superalloys now used in jet engines, are now under development. These will not be available for use unless they undergo several years of additional testing. It has sometimes been proposed that steps be taken to prequalify such low-cobalt substitutes (presumably by government) so that they would be available for use.[34] Because of rapid changes in materials used in jet engines, these substitutes could be partially obsolete by the time they are fully developed. Therefore, other options—ranging from stockpiling to recycling to aggressive pursuit of advanced materials—could be more effective in reducing vulnerability in this application.

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[33] This steel was not developed to reduce import vulnerability, but as part of the breeder reactor program. It is intended to replace both a 2¼ percent chromium steel and a 18 percent chromium steel now used in powerplants, so that the design of a particular powerplant will determine whether more or less chromium is used. It has been speculated that this steel may eventually replace 18 percent chromium stainless steels in some other applications, although, to date, this has not occurred. Federal expenditures in data development and other activities associated with qualification of the material are estimated to be about $5 million since 1978. An estimated $2 million in private services have been donated to the effort. The 9 percent chromium alloy is expected to be used commercially in some applications in 1984.

[34] See, for example, the discussion in U.S. Department of Commerce, *Conservation and Substitution Technology for Critical Materials: Proceedings of Public Workshops*, June 15-17, 1981, p. R1-1.

Fewer options are available for reducing chromium import vulnerability for stainless steel, however, and despite appreciable research efforts, an estimated 40 percent of the chromium used in stainless steel is considered irreplaceable. At present, several low-chromium alloys that could substitute for higher chromium stainless steels in some applications are in the early stages of laboratory development. (Table 7-4 in ch. 7 shows selected examples.) Current substitution research is addressing applications in the midrange of difficulty (technically feasible substitutes could be developed after a period of intensive R&D). Full development of substitutes for this midrange of applications could ease allocation decisions in a supply disruption so that available chromium could be used in those applications for which no alternatives are likely to be available.

Targeting a few of the most promising low-chromium substitutes for augmented development would require in-depth analysis of their current status, needed development steps and associated costs, and applications in which they could reduce critical and strategic material needs. Substantial input from industry, testing societies, and academic institutions would be needed both to identify the most promising materials, and to undertake most of the indicated development steps. Given the costs that could be entailed—the Oak Ridge qualification process discussed above cost an average of $1 million per year over a 5-year period—such a program would have to be conducted at a small scale, with no more than two or three materials undergoing augmented development at any given time.

Ultimately, whether it would be desirable to establish a cooperative government and industry program of this sort depends on the prominence that is assigned to substitution in overall Federal strategies for reducing import dependency. Development of direct substitutes is a medium-term (5 to 15 years) response for reducing import dependency, so that actions taken now will not have an immediate effect. At the same time, it may be difficult to justify Federal applied research on direct substitutes unless the end result is to reduce overall U.S. import vulnerability. This may not occur unless ways are found to develop promising substitutes to the point to which they can be used by industry.

The Potential of Advanced Materials

Strategic materials displacement is not a primary reason for the current interest in advanced ceramics, various composite materials, rapidly solidified alloys, and other advanced materials that are the subject of intensive R&D efforts by government and industry. Rather, these materials promise special performance benefits compared to currently used materials. However, advanced materials usually contain little or no cobalt, chromium, manganese, or PGMs, and therefore, over the long term they have promise to displace or reduce some strategic material requirements. Often, reduced strategic material requirements will be an indirect benefit of using these materials. Since redesign of component systems may be necessary for optimal use of advanced materials, overall savings in strategic materials are difficult to predict.

Advanced materials—unlike direct substitutes for currently used materials—have the potential to provide the basis for important new U.S. industries, while at the same time reducing requirements for strategic materials in some applications. Advanced ceramics may become a multibillion dollar business, with potential markets projected to reach over $20 billion by the year 2000. However, at present, the competitive posture of the United States in advanced ceramics lags behind Japan in the area of electronic components, and the United States is in some danger of losing the race for market supremacy in engineering ceramics. Other countries, including Great Britain and some Western European countries, are also vying for expanding world markets.

A 1984 Commerce Department study of the advanced ceramics industry indicated that neither the United States nor Japan was in the clear lead with regard to advanced ceramic engineering materials. However, the Department predicted that the United States could fall behind Japan if current trends continue. Japanese success was noted in the following areas:

- domination of electronic components made of advanced ceramics;
- domination of supplies of advanced ceramic powders;
- greater and more organized R&D efforts;
- superior performance/cost characteristics of Japanese demonstration products;
- reputation for accepting short-term losses and investing in long-term product-market development; and
- record in developing and implementing superior commercial manufacturing processes and technologies.[35]

The potential importance of an internationally competitive advanced materials industry to the U.S. economy, and the stance of the Federal Government in encouraging such industrial activities, is likely to be an increasingly visible issue in the years to come. In general, the alternative roles that the government could play in fostering a strong domestic ceramics industry are likely to be identified and debated within the broader context of the overall posture of government-industry relations, not in the context of strategic material issues. Regardless of the extent of government involvement in encouraging U.S. competitiveness in this area, a number of technical and institutional problems will have to be overcome before these materials come into general use. Therefore, the discussion here is focused on issues of Federal involvement in research, development, information transfer, and education, rather than on the full spectrum of alternative policies to encourage advancement of this sector of the economy.[36]

Government Support of Research and Development

It is generally thought that the United States leads the world in basic research with regard to advanced materials. Funding of advanced materials R&D activities in the United States appears to be generally healthy. However, continuation of a strong basic research effort will probably be needed for many years. Manufacturing processes and fabrication technologies are areas in which more emphasis in R&D is generally considered necessary. The high costs of fabricating composites, for example, arises in part from labor-intensive and time-consuming processes. In advanced ceramics, key needs are to improve powder production and to develop reliable processing technologies to produce flaw-free ceramics economically. Improved nondestructive evaluation techniques are critically needed in both composite and ceramic applications.

As with other areas of material research, several Federal agencies, including NASA, NBS, the Bureau of Mines, various Defense Department agencies, and the DOE national laboratories, undertake or sponsor advanced materials research. Much of the government research is undertaken on a contractual basis with industry. Information sharing among researchers, including various government agencies and those firms directly involved in R&D, is generally considered by researchers to be effective. However, coordination of policy with respect to advanced materials, particularly at high levels of the executive branch and with Congress, has been fragmented.

As discussed previously, the National Critical Materials Act of 1984 calls for the establishment of a "national Federal program for advanced materials research and development," giving key responsibility to the National Critical Materials Council in the Executive Office of the President for implementing the program.

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[35] U.S. Department of Commerce, *A Competitive Assessment of the U.S. Advanced Ceramics Industry* (Springfield, VA: National Technical Information Service, 1984), p. 64.

[36] Readers who are interested in alternative Federal roles in strengthening the international competitiveness of the U.S. advanced ceramics industry are referred to the Commerce Department's assessment identified in the previous footnote. The broader issues associated with alternative government actions involving transfer of new technologies to the private sector are discussed in "Development and Diffusion of Commercial Technologies: Should the Federal Government Redefine Its Role?" (Office of Technology Assessment Staff Memorandum, Industry, Technology and Employment Program, March 1984.)

The Council, among other things, is directed to prepare and annually review a Federal program plan for advanced materials R&D. The plan is to designate key responsibilities for carrying out research, and is to provide coordination with the Office of Management and Budget, the Office of Science and Technology Policy, and other appropriate Federal offices and agencies.

The Council is also to review annually the materials research, development, and technology budget requests of all Federal agencies to ensure close coordination of the goals and directions of such programs with policies determined by the council. The Office of Management and Budget, upon reviewing individual agency budget requests, is to consider them as an "integrated, coherent, multiagency request" to be reviewed by the Council and OMB for adherence to the national Federal materials program plan for each fiscal year.

The process established by the 1984 Act can be expected to give far greater visibility to research needs associated with advanced materials than has existed heretofor. However, in keeping with the process orientation of most congressional laws pertaining to materials R&D, the law gives the Council considerable discretion in putting together components of the plan. For example, while the law makes it clear that the program is to include R&D from "basic phenomena" through processing and manufacturing, it does not define the term "advanced materials," thus giving the Council flexibility in determining which classes of materials fall under the program plan. The Council will also have discretion in determining overall goals and objectives of such a plan. As a result, congressional oversight and guidance may be needed to determine whether the Council's program accurately reflects Congress' intent in establishing the program (table 8-8, issue 3).

Education Needs and Advanced Materials

Considerable concern exists about the adequacy of current engineering curricula and training of engineers and designers in the use of advanced materials. Most curricula in engineering schools are designed to familiarize engineers with materials that are most prevalently used *today*, such as metals. Progress in advanced materials fields—the materials which will come into greater prominence in the future—may hinge in part on the success of engineering curricula to make engineers and designers familiar with processing technologies, and product design associated with advanced materials. Although many U.S. universities are important research centers in one or more advanced material areas, U.S. universities are turning out comparatively few people in some advanced materials fields. In the area of ceramics, for example, only 36 identifiable doctorates were estimated to have been granted in the 1982-83 school year by U.S. universities.

The Federal Government can assist U.S. universities to increase their emphasis on advanced materials if it so desires. Various assistance programs administered by the National Science Foundation, and academic research and curriculum development activities supported by other Federal agencies could be used to channel increased support for advanced materials activities in universities.

One option would be to provide initial educational development grants to several universities for a specified time period (e.g., 5 years), after which time the university would assume full responsibility for the program. Because these programs could have clear benefits to private industry, industry might contribute to such an effort. The startup funds could be used to attract new faculty, support research, assist in acquisition of needed instruments, or participate in other activities that would be needed to establish a sound curriculum and research program. Industry-university cooperation and coordination could be encouraged through advisory committees comprised of industry and government representatives and through internships and collaborative research projects.

Transfer and Diffusion of Advanced Materials Technologies

Advanced materials are currently in an early stage of commercial application. A key issue in their ultimate acceptance and adoption by industry on a widespread basis will be the extent to which reliable engineering data (including clearly defined procedures for testing materials), materials specifications and physical property data, and standards can be developed in a form that is readily accessible to users.

As discussed in chapter 7, current U.S. problems in maintaining an upgraded materials property data management system in general are acute. In the case of many advanced materials, including rapidly solidified metals, ceramics and some composites, absence of accessible information is a major constraint to their widespread use. Data on advanced materials is held largely by the research community and by the few firms that have been integrally involved in their early development or that have proprietary data for specialized applications. A kind of catch-22 is involved in this situation: designers will not use new materials until they have data on their behavior in engineering applications, but until the materials are used by designers, that data will not exist.

The formal codes, reliability standards, specifications, and other forms of information that would aid product design engineers select materials are not generally available for advanced materials. Development of such information will be a long-term process, and it may be many years before general agreement is reached about the proper form of such information.

Although testing societies, private industry, and trade associations, generally determine material standards, the Federal Government can play an important facilitating role if it chooses. Several Federal agencies, including the Department of Defense, DOE, NBS, and NASA all have important programs related to advanced materials, and have been integrally involved in maintaining materials data bases that could be of considerable relevance to standard-setting activities.

A cooperative effort by government and industry to undertake initial work to develop organizing concepts, define information needs, and identify appropriate formats for needed engineering data could be an important preliminary step toward advanced material standard-setting. Such a cooperative endeavor would require extensive interactions between testing societies, industry, academia, and government, with each contributing key inputs to the process. One possible arrangement (table 8-8, issue 4) for facilitating such interaction would be for the Federal Government to partially sponsor (with contributions by relevant industries) a nonprofit center associated with a testing society, a university, or other nonprofit institution. A similar approach is being used to explore the feasibility of establishing a national materials properties data network with primary reference to metals.

Conservation and Recycling of Strategic Materials

OTA's analysis indicates that ongoing trends in industry have led to more efficient use of materials in processing and manufacturing. These trends are expected to continue as firms upgrade facilities and adopt new manufacturing processes.

In steelmaking, for example, manganese requirements for each ton of steel produced are expected to be reduced from 36 to 25 pounds by the year 2000. Somewhat greater savings (in terms of imported manganese) are likely because of increased use of scrap and improved manganese recovery rates. Near-net shaping processes used in the areospace industry will also reduce cobalt raw material requirements for superalloy production, although this will also be accompanied by a reduction of home and prompt industrial scrap preferred for recycling. The incentive to conserve PGMs is very high, owing to their high cost; thus, improvements in catalyst design that would reduce PGM use can be expected to be adopted quickly. Some modest improvements in chromium utilization can be expected, but the rapid phase-in of the argon-oxygen decarburization (AOD) process in making stainless steel is now nearly complete, and no major breakthroughs appear imminent. As a rule, material-conserving technologies will be adopted because of product quality and cost competitiveness reasons, not because of concern about strategic materials.

Important opportunities also exist to increase supplies of cobalt, chromium and PGMs through recycling. In the case of PGMs, the chief opportunity for increased secondary production is through recycling of automotive catalysts; an emerging industry structure is developing to collect and process these catalysts. Opportunities to extend cobalt supplies include improved recycling of cobalt values from obsolete superalloy scrap and recovery of cobalt from spent catalysts used by the petroleum industry. Although stainless steelmakers now derive one-fourth of their chromium needs from purchased scrap, losses from three areas—downgrading, failure to recover obsolete scrap, and losses of chromium in steelmaking wastes—are substantial. See table 6-6 in chapter 6 for a detailed listing of recycling opportunities.

Increased recycling not only augments strategic material supplies, but also has environmental benefits associated with reduced landfilling and disposal of wastes. Recycling also offers energy conservation benefits, since scrap already embodies initial energy requirements needed to process raw ores into concentrated form. Energy savings from recycling aluminum scrap, compared to manufacturing the same product from virgin materials, can exceed 90 percent, and for copper, iron and steel, lead, and zinc, savings of over 60 percent have been noted.[37] Because the first-tier minerals covered by this report are produced and often partially processed abroad, net energy savings to the U.S. from increased recycling of these materials would only accrue as an alternative to increased domestic production, however.

Economic barriers (arising from the added cost of collecting, sorting, transporting, and reprocessing obsolete scrap and waste) and institutional impediments (e.g., difficulties in organizing collection systems and the reluctance of consumers to use recycled materials) are the major constraints on recycling.

Appreciable advances in recycling technologies have been made in recent decades, owing in part to Bureau of Mines' R&D efforts, and industry initiatives. In general, few technical problems need to be overcome to increase recycling of PGMs, cobalt, and chromium. However, in some applications—especially superalloys—advanced technologies may have to be developed before major advances can be made in current levels of recycling. Increasing complexity in materials used in products in general also means that continuing R&D will be needed to meet future recycling needs.

OTA's analysis of recycling issues focused on several areas of possible congressional concern: adequacy of information about current and prospective levels of recycling; the need for evaluation of the indirect effects of Federal programs and policies on recycling in order to identify possible changes that could facilitate recycling; and the possible need of a pilot plant project to demonstrate advanced superalloy recycling technologies. These issues, and associated options, are summarized in table 8-9 and discussed below.

Information Needs and Recycling

Recycling's potential to reduce import dependency can only be roughly estimated unless reliable information is available about both current levels of recycling nationwide and about quantities of unrecovered scrap and waste that could potentially be recycled if economic or technical conditions changed. Current statistical series provide incomplete information about annual levels of recycling because they focus on the purchased component of scrap supplies, and do not estimate potentially recyclable materials that are not recovered. Increased emphasis on compilation of recycling data and trend analysis seems needed if policymakers are to have a realistic picture of the prospective role that recycling could play in reducing U.S. dependency on imported materials (table 8-9, issue 1).

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[37] National Association of Recycling Industries, *Recycled Metals in the 1980s* (New York: National Association of Recycling Industries, 1982), p. 174.

From time to time, agencies such as the Bureau of Mines and the National Materials Advisory Board have produced relatively comprehensive materials flow models for individual metals or applications. These models have appreciably increased understanding of overall recycling levels, but have been prepared infrequently, with little or no followup or consistency in procedures used. The need for materials flow information is especially apparent in the area of superalloy recycling—an area that changes rapidly, affects use of several strategic materials, and is of obvious importance to national security. Most current information about the flow of superalloy scrap is based on conditions in 1976—the last year for which a comprehensive materials flow model for superalloy scrap was prepared by the government. Efforts to update this model using 1980 data—but 1976 scrap ratios—do not fully reflect the important changes that have occurred in superalloy recycling since then.

Analysis of long-term trends in conservation and recycling is also needed on a periodic basis, especially since the two often influence each other in complex ways. Adoption of near-net shape technologies by aerospace manufacturers will reduce the amount of preferred scrap generated in the fabrication of superalloy parts. This means that obsolete scrap and lower quality manufacturing scrap will comprise an increasing portion of the materials potentially available for recycling. Similarly, efforts such as the Air Force retirement-for-cause program to extend the life cycle of jet engine parts could reduce the amount of obsolete scrap available

Table 8-9.—Policy Alternatives for Recycling Strategic Materials

		Arguments for/against	
Problem/issue	Option	Positive	Negative
1. Annual statistical series do not provide an adequate picture of current and prospective recycling levels; detailed information is out of data and not prepared on a regular schedule.	Supplement current data with in-depth "cradle-to-grave" data and analysis of Cr, Co, Mn, and PGM or other materials as appropriate on a regular schedule.	Better information about recycling is needed for realistic appraisal of recycling's prospective role in reducing import dependency.	Could add to industry paperwork requirements.
2. Adjustments in Federal programs and policies could encourage greater recycling of strategic materials, but the necessary evaluation of these programs has not been done by the Administration.	Call for an executive branch evaluation, with recommendations to Congress, about ways to structure Federal programs related to taxation, real property procurement and disposal, environmental regulations, etc., to encourage strategic materials recycling.	Could lead to eventual changes in Federal programs which would be helpful to recycling firms in increasing recycling levels.	Federal Government should not attempt to favor one mineral form over another; overemphasis on recycling could inhibit domestic mining activities related to strategic materials.
3. Advanced recycling technologies for superalloys may not be developed by private industry because of low metal prices.	Authorize one or more pilot-plant projects to demonstrate technical feasibility of reclaiming individual elements from superalloy scrap or other advanced scrap recovery processes.	If technical merit of research processes is demonstrated in pilot project, it may be possible to recycle most of the superalloy scrap that is now downgraded or lost. (An estimated 2.8 million pounds of cobalt was lost in superalloy scrap alone in 1980.)	Option provides less immediate supply security than domestic production and depends on successful outcome of pilot project to determine commercial feasibility; government should not be involved in commercialization of new technologies.

SOURCE: Office of Technology Assessment.

for recycling. These interrelationships are discussed in greater detail in chapter 6.

Superalloy applications are not the only area where current data are inadequate for identifying current and prospective recycling levels. Opportunities for recovering more chromium from obsolete stainless steel products and steelmaking wastes can only be roughly estimated since most of the available national data date from 1976 and 1974, respectively. Important improvements have occurred since then. Similarly, monitoring of PGM recycling from automotive catalysts and electronic scrap will clearly have to be emphasized in the years to come in order to develop accurate information about recycling trends in this industry.

Analysis of industry trends and the revision of scrap material flows on an annual basis is probably not necessary or desirable, but it would be desirable on a periodic basis, perhaps once every 4 or 5 years. The Bureau of Mines, which sponsored the superalloy analysis discussed above as well as a similar scrap flow model of chromium recycling in stainless steel, would be a logical agency to undertake this analysis. Cost of preparing new material flow models would vary, but would probably be less than $100,000 per application addressed. The original appropriation for the two models mentioned above was provided to the Bureau of Mines under the Defense Production Act through the Federal Emergency Management Act. Update of these models would cost about $50,000 per application.

At present, limited national level information is available about "hidden inventories" of strategic materials that could potentially be recycled in the event of a supply disruption. (Stockpile management estimates about recycling levels in a supply disruption are based on economic analysis, not estimation of materials.) Hidden inventories include scrap inventories that for one reason or another are not reported to the Bureau of Mines and potentially reclaimable mining tailings and industrial waste materials. Such inventories can be quite large. At one Gulf area petroleum catalyst recycling operation, for example, perhaps as much as 7 million pounds of cobalt-nickel aluminate slag has accumulated over the years. This material would not be economic to recover without major increases in cobalt prices, and some technical problems in recovery would have to be overcome. In a supply disruption of protracted length, however, it may represent a recoverable resource. In addition, a large quantity of strategic materials are present in mine tailings which may be potentially reclaimable. Although information is available about strategic material content of some of these tailings (e.g., cobalt tailings from lead zinc mining in Missouri), their national magnitude is not known accurately.

The importance of information can, of course, be overstated. It would not be necessary, or even desirable, to attempt to inventory comprehensively all low-grade sources of strategic materials, for example, to derive plausible estimates of the magnitude of such resources. Nor are current information deficiencies so great as to prevent identification of applications and materials in which there is potential for major increases in current recycling levels. However, an institutional mechanism for periodic reexamination of recycling and conservation trends and opportunities would be highly useful in policy formulation.

The Impacts of Federal Activities on Recycling

The Federal Government influences recycling of strategic materials both directly and indirectly. Direct effects arise from its R&D activities aimed at improving recycling technologies. This research has had a demonstrable effect in encouraging increased recycling of strategic materials; many currently used processes were initially developed with Federal support.

Indirect effects—some positive and some negative—arise from a wide variety of Federal policies and programs that are not specifically aimed at recycling. Such activities as taxation, regulation of transportation rate setting, environmental policy, and procurement and disposal of materials by Federal agencies can affect material flows in the economy. Several recent laws have attempted to remove inadvertent bias in Federal regulations that may favor virgin raw materials over recycled materials, but the recycling industry continues to be concerned that Federal policies may discourage recycling.[38]

The National Materials and Minerals Policy, Research and Development Act called on the President to:

> . . . assess Federal policies which adversely or positively affect all stages of the materials cycle, from exploration to final product recycling and disposal including but not limited to, financial assistance and tax policies for recycled and virgin sources of materials and make recommendations for equalizing any existing imbalances, or removing any impediments, which may be created by the application of Federal law and regulations to the market for materials . . .[39]

The President's materials plan did not specifically address this issue. (The plan placed such analysis in the overall context of its regulatory reform assessment, an approach that is not specific enough to suggest improvements for strategic materials recycling.)

Such an evaluation and recommendation process—especially if focused on strategic materials—could help identify possible changes in Federal programs that could encourage greater or more effective recycling of strategic materials (table 8-9, issue 2). This cannot be done with a narrow focus simply on strategic materials: overall objectives and missions of Federal programs must be taken into account, even if a particular program or policy may adversely affect recycling.

Nonetheless, there may be ways to encourage recycling while meeting these broader objectives. One area meriting further examination concerns possible connections between waste disposal policies and recycling. Spent cobalt-molybdenum hydroprocessing catalysts, for example, may contain trace amounts of lead and arsenic that may make them potentially hazardous. Although spent catalysts are not a listed hazardous waste, generators of spent catalysts often treat them as such, and as potentially subject to Federal regulations which restrict storage of hazardous wastes on site to 90 days. As a result, within 90 days, generators of spent catalysts must decide whether to send the material for recycling or to landfill the material at an approved site. In the late 1970s, recyclers of spent cobalt catalysts would often pay generators $300 per ton to obtain this material in order to recycle molybdenum. In the 1982-83 period, generators often needed to pay the freight to have the spent catalysts sent to the single U.S. firm still recycling those catalysts for molybdenum values. As a result, landfilling is often a more attractive option, and simply storing the material on site while waiting for metal values to increase is precluded. An estimated 270,000 pounds of cobalt were not reclaimed from spent hydroprocessing catalysts in 1982.

The impediments to recycling cobalt catalysts are thus largely economic in nature, arising from the low value of metals at the present time, but Federal hazardous waste regulations may inadvertently cause premature loss of cobalt values. It would be inappropriate to change Federal policy with respect to hazardous waste simply to facilitate recovery of strategic materials in circumstances such as this. However, with appropriate safeguards, it may be possible to develop alternatives to encourage recycling of strategic materials while safeguarding concerns about public health and safety arising from hazardous waste storage. Possible alternatives to encourage recycling of strategic materials from some hazardous waste include intensifying the recycling R&D activities by the Bureau of Mines to assist industry in developing effective reclamation technologies; possible use of guaranteed purchase agreements under the Defense Production Act to defray the expense of reclamation when it is currently not economic; longer term but temporary storage of some hazardous wastes containing strategic materials in regional repositories where they would be available for subsequent recycling; and possible use of "waste end" taxation, which could make landfilling less attractive as a disposal option by taxing generators of wastes when they are landfilled.

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[38] For a discussion of the concerns of the recycling industry about Federal policies, see National Association of Recycling Industries, *Recycled Metals in the 1980s* (New York: National Association of Recycling Industries, 1982), pp. 167-177.

[39] Public Law 96-479, sec. 4(8).

Increasing interest exists in strategic material recycling opportunities associated with surplus Federal property—especially that of the Department of Defense. GAO is currently auditing Department of Defense scrap generation levels and possible alternative means of disposal of scrap at the request of the House Armed Services Committee. However, the GAO effort is focused principally on aluminum—not on superalloy scrap.

Military aircraft contain large quantities of strategic materials that are potentially recyclable at the end of their service life. Currently, most jet engine parts are declared surplus and are sold as scrap at the end of their useful service life. Generally, obsolete superalloy scrap is downgraded for its nickel and chromium content, so that other metals (e.g., cobalt) are not beneficially used.

Alternatives to disposal of surplus scrap could have strategic material conservation benefits. The Department of Defense and the General Services Administration can promote advancement of recycling technologies and processes by contributing surplus scrap to demonstrate advanced recovery methods.

A model and precedent for a government-run recycling program exists. For nearly a decade, the Department of Defense has conducted a precious metals recovery program (including platinum, palladium, and rhodium) from surplus, damaged, or outdated government property. The recycled materials are refined to a high level of purity and may then be used as government-furnished materials in defense contracts and in certain other government contracts. Savings to the government from this program have been very large because the costs of recovering and refining PGMs are cheaper than purchasing new material.

At current cobalt prices, this would not be the case with regard to superalloy reclamation. An Air Force working group established to assess a feasibility study on a cobalt reclamation process for obsolete jet engine parts reached the conclusion that it would be cheaper for the government to sell these parts as scrap, given current cobalt prices. (The working group did not identify costs associated with the various alternatives.) This argument fails to take into account the strategic benefits of having a domestic capability to reclaim individual elements from scrap in the event of a supply emergency.

Besides evaluation of agency programs to determine whether changes may be needed in Federal policies with respect to recycling, the Federal Government can heighten visibility of recycling industry issues through special studies.

The National Materials and Minerals Policy, Research and Development Act of 1980 established a continuing assessment function in the Commerce Department to undertake case studies of specific material needs to ensure "an adequate and stable supply of materials to meet national security, economic well-being and industrial production needs." To date, studies have been completed on the steel industry, and the aerospace industry, and a study on the domestic mining industry is in progress. Although such studies may address recycling to some extent, special assessment of key components of the recycling industry would aid in understanding the role recycling could play in providing strategic and critical materials and in the identification of economic and institutional barriers to increased recycling.

Developing New Recycling Technologies

Recycling of strategic materials often entails highly sophisticated technologies and processes. The increasing complexity of materials used in end products, such as jet engines and automobiles, and the general trend toward more stringent material specifications, require adjustments in segregating and processing scrap by recyclers. As a result, extensive R&D activities are often needed to keep pace with changes in end products.

Substantial technical advances have been made in recycling technologies in recent years, and many of these advances have been supported by government research. Increasingly, as government funds for general recycling research have become more limited, available funds have been targeted on strategic materials, including processes and technologies to effectively reclaim them from low quality materials (e.g., obsolete scrap) that are not now processed.

Several Federal agencies, including the Department of Defense, NASA, and the Environmental Protection Agency, have sponsored recycling R&D activities relevant to strategic materials. However, the Bureau of Mines is the primary Federal recycling research agency. Recent Bureau projects have emphasized, among other things, development of processes to enhance recovery of cobalt, nickel, and chromium from materials such as superalloys and stainless or specialty steel scrap and wastes. Funding of strategic materials recycling activities has been maintained at a high level through reprogramming of funds from other areas.

Normally, industry itself assumes the key role in actually developing new technologies arising from Bureau research. Many currently used processes pertaining to recycling of steelmaking wastes, cemented carbides, and other materials were originally developed or sponsored by the Bureau of Mines. At least seven companies, for example, are using a Bureau-patented process which permits effective recovery of cemented carbide scrap, with its cobalt values.

Current metal prices do not justify private investment in post-laboratory development of some experimental recycling technologies—especially those for superalloys—that promise to substantially improve recycling of strategic materials. Superalloy raw materials provided through recycling will increasingly depend on effective obsolete scrap recovery since manufacturing processes are reducing the amount of home and prompt scrap available.

Several commercially used processes can be, and to a limited extent have been, used to recycle obsolete superalloy scrap to provide master melts suitable as raw materials for jet engine superalloys. Alternative processes that reclaim individual elements from the scrap in highly purified form have been demonstrated only in the laboratory.

Experimental reclamation processes of this sort have been developed under Bureau of Mines' sponsorship, and independently by some companies. Proof that they would work in commercial-scale operations has not been ascertained, and an additional 2 to 5 years of work may be needed to reach definitive conclusions.

One Bureau-sponsored experiment, undertaken in the late 1970s, demonstrated the technical feasibility of separately reclaiming individual elements from superalloy scrap, including cobalt, chromium, and nickel—an important breakthrough if the technical merits of the process hold up outside of the laboratory. Industry feasibility studies for a pilot plant and small commercial facility showed promising profit potential at 1980 prices (cobalt was then selling at $25 per pound), but when prices fell, so did interest in the project. (The price of cobalt that would allow this process to break even is confidential information with the company that developed the feasibility study.) Other Bureau of Mines' processes, including one which rapidly dissolves metals out of the superalloy scrap, may also have the potential to advance superalloy recycling technologies. Some private firms, as discussed in chapter 6, have undertaken laboratory research in the area of reclamation. One of these firms currently recovers cobalt from various scraps (including superalloy grindings) for use in cemented carbides, and is considering possible applicability of the process for recycling superalloys per se.

Although government's role in commercializing specific new technologies is usually limited, overriding national objectives, such as national security, may justify exceptions. Further development of advanced superalloy recycling processes may well be such a case. One alternative would be for government (in consultation with industry to select the most promising candidate processes) to sponsor one or more pilot plant projects to demonstrate advanced reclamation processes—either at a government facility or under contract with industry (table 8-9, issue 3). The costs of a pilot plant project, probably entailing $5 million or more per project facility plus $1 million to $2 million in operating costs, need to be viewed in terms of the potential benefits and increased supply security that could accrue to the United States in the event that such technologies are commercially viable. Commercial availability of such technologies could give U.S. firms the technical capability to recycle most of the cobalt that is now lost or downgraded, estimated at 2.8 million pounds in 1980.

Appendixes

Appendix A

Review of Previous Lists and Methods of Selection

Most lists of strategic materials are based, implicitly at least, on the two strands of criticality and vulnerability. A 1981 report by the Congressional Research Service listed the following criteria for defining a materials import "vulnerability" (as distinguished from import "dependency"):[1]

1. Critical need for the material.
2. Lack of adequate domestic resources (including both a total lack and an insufficiency).
3. Limited potential for substitution.
4. Lack of alternative sources of supply (including politically stable sources and geographically close sources).

It will be noted that factors (1) and (3) have to do with criticality of use, and factors (2) and (4) with vulnerability of supply. On the basis of these factors, the Congressional Research Service defined the following as "materials of particular concern":

Bauxite/aluminum
Cobalt
Chromium
Columbium
Manganese
Platinum-Group Metals
Tantalum
Titanium

A "semiquantitative" index for rating strategic materials on the basis of vulnerability was devised by the Strategic Studies Institute (SSI) of the U.S. Army War College in 1974.[2] The index was based primarily on five factors affecting vulnerability to "coercive pressures from foreign suppliers," as follows:

1. Availability of domestic reserves.
2. Availability of substitutes.
3. Number and location of foreign suppliers.
4. Ideology of foreign suppliers.
5. U.S. stockpile objectives (based, at that time, on 1 year's wartime needs).

Materials selected for the SSI assessment were the 20 minerals for which the United States imported half or more of its requirements, plus tungsten. The authors included tungsten, even though U.S. import dependency for tungsten was below 50 percent, because the ratio of U.S. production to consumption was "rapidly decreasing" and because of "the unusual circumstances that the Communist countries possess about 75 percent of world reserves."[3]

Of the 21 materials. 10 were eliminated "because of favorable combinations of such factors as adequate U.S. reserves, declining domestic demand, available substitute materials, availability of technology to process low-grade ores, and proximity of foreign supplies."[4] The other 11 minerals were assigned index numbers and ranked by relative vulnerability, as shown in table A-1.

The SSI does not describe exactly how the index numbers for each material were derived. The text implies that the index numbers are the sum of numerical values assigned (on the basis of the authors' judgment) to each of the five principal factors mentioned above. The selection of these factors gives far more weight to vulnerability of supply than to criticality of use. However, it is evident from the text that factors other than those five entered into the ratings. For example, the authors' discussion of individual materials refers to the essential uses of each, as well as the availability of substitutes. In any case, as the authors state, the numbers do not refer to anything quantitative but were based on "qualitative assessment," that is, their own judgment.

In 1977, one of the authors of the SSI study revised the vulnerability index in an attempt to refine it and make it more quantitative.[5] The 1977 version of the SSI Index included 27 factors, each rated for the importance of its influence on economic, political, and military vulnerability of materials. Table A-2 shows the factors and their ratings.

Of the 27 factors on the list, no more than 5 are related to criticality. Not one explicitly mentions the essential uses of particular materials. Yet one must assume that essential uses are implicit in the rating scheme, at least in the selection of materials to rate and in assessing the availability of substitute materials.

A further complication in the rating scheme is that each of the 27 factors is also assessed for the

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[1] Congressional Research Service, *A Congressional Handbook on U.S. Materials Import Dependency/Vulnerability*, cited in note 2, p. 341 ff.

[2] Alwyn H. King and John R. Cameron, *Materials and the New Dimensions of Conflict*, Strategic Studies Institute, U.S. Army War College (Carlisle Barracks, PA: 1974) available from National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22151 (AD/A-004263).

[3] Ibid., p. 5. 1981 estimates indicate that China holds 47 percent of the world reserve base of tungsten, and another 11 percent is in the Soviet Union and North Korea. Both Canada and the United States have large reserve bases of tungsten; Canada's is 15 percent of the world trade.

[4] Ibid.

[5] Alwyn H. King, Materials Vulnerability of the United States—An Update, Strategic Studies Institute, U.S. Army War College (Carlisle Barracks, PA: 1977), available from the Defense Technical Information Center, Defense Logistics Agency, Cameron Station, Alexandria, VA 22314.

Table A-1.—Strategic Studies Institute Index of Relative Vulnerability: 1974 Ranking

Material	Vulnerability index	Principal or major exporters
Chromium	34	Soviet Union, South Africa
Platinum metals	32	Soviet Union, Canada, South Africa
Tungsten	27	Canada, Peru
Manganese	23	Brazil, Gabon
Aluminum	22	Jamaica, Canada
Titanium	20	Australia, Canada
Cobalt	20	Canada, Zaire
Tantalum	16	Canada, Brazil, Zaire
Nickel	14	Canada, Norway
Mercury	11	Canada, Mexico, Spain
Tin	6	Malaysia, Thailand

SOURCE: Alwyn H. King and John R. Cameron, *Materials and the New Dimensions of Conflict*, Strategic Studies Institute, U.S. Army War College (Carlisle Barracks, PA, 1974)

Table A-2.—Factors Affecting Materials Vulnerability Index: 1977 List

	Effect on Vulnerability		
Factor	Economic	Political	Military
Domestic reserves:			
Availability	L	L	L
Cost of developing	L	L	S
Domestic production industry:			
Present capability	L	L	L
Cost of augmenting	L	L	S
Substitute materials:			
Present availability	L	L	L
Cost of research to develop	L	L	S
Time required to develop	L	L	L
Additional domestic resources:			
Present availability	L	L	L
Cost to develop suitable processes	L	M	M
Time to develop suitable processes	M	M	M
Probability of discovery if not available	M	M	S
Cost of additional exploration	M	M	S
Foreign suppliers:			
Number of controlling companies	L	S	M
Number of supplier countries	M	M	M
Political stability of supplier countries	M	L	M
Ideology of supplier countries	M	L	M
Productive capacity of supplier countries	L	L	L
Economic sufficiency of supplier countries	L	L	S
History of political relations with U.S.	S	M	S
U.S. dollar involvement in supplier country	M	M	S
Accessibility of supplier countries (supply routes)	S	S	L
U.S. stockpile:			
Present U.S. stockpile objective	L	L	L
Actual quantity in U.S. stockpile	M	M	M
Customary industry stockpile	M	M	M
Trend in usage of critical material	M	M	S
Proportion of national consumption directly related to military requirements	S	S	L
Importance of secondary sources (recycling)	M	M	M

KEY: L = Large
M = Medium
S = Small

SOURCE: Alwyn H. King, *Materials Vulnerability of the United States—An Update*, Strategic Studies Institute, U.S. Army War College (Carlisle Barracks, PA: 1977).

direction of its influence on vulnerability; that is, whether it currently contributes to a significant increase, a moderate increase, or a decrease in the vulnerability of material supplies. All these factors, including their importance and direction, are given numerical values, the sum of which is the "relative vulnerability index" number of each material. Figure A-1 shows the results for four materials.

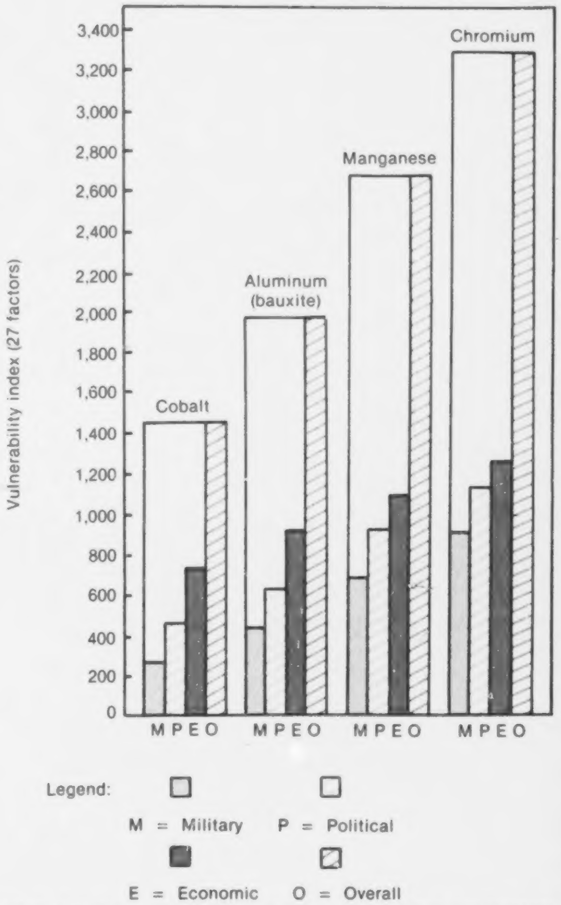
The authors suggested using this numerical index to help set priorities for stockpiling, allocation of funds to research and development, and other such decisions. A pitfall in using this index, or others like it,[6] for such purposes is that it may convey a misleading impression of certainty or objectivity. The use of index numbers to show "relative vulnerability" may be a convenience but does not at all evade the necessity of applying subjective judgment—as the authors of the index recognized. Judgment is involved at every step: in deciding what factors to include, how much importance each should be given, how to rate a material in relation to a specific factor (e.g., "political stability of supplier countries"), and so on.

Another attempt to construct a systematic rating system for strategic materials was the Critical Minerals Index pilot study done by the U.S. Department of the Interior's Office of Minerals Policy and Research Analysis in 1979.[7] Designed to be used as warning of potential problems, the index included two components: one to measure the likelihood of disruption of supply (i.e., vulnerability) and the other to measure the cost of disruption or, conversely, the importance of the minerals to the U.S. economy (including factors of vulnerability and criticality). The scheme proposed to use the subjective judgment of a panel of experts to assign index numbers for both components to specific minerals.

Examples of events considered possibly disruptive to supply were:

- Collusive price agreements (cartels).
- Shifts in demand.
- Embargoes.
- Labor strife.
- Transportation bottlenecks.
- Violent conflicts, including local rebellion, regional war, riots, border skirmishes, blockades, and sabotage.

Figure A-1.—Strategic Studies Institute Relative Vulnerability Index: 1977 Ranking



NOTE: Overall index number is the sum of military, political, and economic index numbers.

SOURCE: Alwyn H. King, *Materials Vulnerability of the United States — An Update*, Strategic Studies Institute, U.S. Army War College, (Carlisle Barracks PA: 1977).

Factors suggested for inclusion on the cost side were:

- The magnitude and duration of the disruption.
- Total annual U.S. demand for the mineral.
- Availability of alternative sources of supply; e.g., domestic or other foreign sources.
- Time required to deliver alternate supplies.
- Availability of substitutes.
- Time required to adopt substitutes.
- Expectations of those controlling investment about the future of alternative supplies and of substitute technologies.

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[6] An index with some similarities to the Strategic Studies Index, with a clearer description of how it is constituted, is in Bohdan O. Szuprowicz, *How to Avoid Strategic Materials Shortages* (New York: John Wiley & Sons, 1981), p. 8ff and p. 285 ff.

[7] Robert L. Adams, Barbara A. White, and James S. Crichar, *Developing a Critical Minerals Index: A Pilot Study*, Office of Minerals Policy and Research Analysis, U.S. Department of the Interior, July 1979.

The Critical Minerals Index was simply proposed in a pilot study. Its authors did not apply it to produce a list of minerals.

A different approach to a rating system for strategic materials, making no attempt to produce overall index numbers, was proposed by the British Institute of Geological Sciences (IGS) in a 1982 Memorandum to a Committee of the House of Lords in Parliament.[8] Dividing the factors that define a strategic material into the vulnerability and criticality strands, the institute's vulnerability list included:

1. Import dependence (besides net import dependence, this factor included total import dependence, recognizing that some of Britain's minerals processing and export industry relies entirely on the import of raw materials).
2. Concentration of supplies to Great Britain.
3. Concentration of world production.
4. Indirect import dependence, involving a long, complex chain of supply.
5. Concentration of world reserves (or "economic resources").
6. Reliability of producer countries.
7. Market mechanisms, which include:
    - the lead time to develop new productive capacity.
    - the proportion of materials tied up in long-term contracts, compared to the amount available on the "free" market.
    - the potential for cartel formation, on the basis of shared interests and values of producers.
8. The potential for recycling.
9. The adequacy and security of supply links on land and sea.

The IGS memorandum pointed out that many of the measures for vulnerability can be quantified, some quite simply. To show the concentration of suppliers to Great Britain, the IGS devised an index based on the total number of supplying countries and the share they supply; the same kind of index was used to denote concentration of world production. Reliability of supply, on the other hand, cannot be quantified because it depends on such considerations as political stability, ideology, or "excessive economic nationalism," which are matters of qualitative judgment.

On the criticality side, the institute mentioned the range of uses, the availability of substitutes, the nature of British industries consuming the material, and a number of measures of the economic importance of the material, all of which, the IGS conceded, were difficult to analyze and apply.

Altogether, the IGS concluded that criticality cannot be quantified readily. The quantitative pointers are either crude or trivial. The more important questions—defining the national interest, judging the importance of one manufacture in relation to another, determining whether substitutions for a material are possible and how long it would take to effect substitutions— are all matters of judgment. However, it is possible to combine judgments about these factors into a subjective criticality rating of high, medium, or low for each material.

Overall, the IGS rating scheme separated the vulnerability and criticality strands; disentangled factors which can be quantified from those which cannot; quantified different factors, each in its own terms; and gave subjective ratings to factors that cannot be measured adequately by quantitative indicators. No effort was made in the scheme to combine all these unlike "apples and oranges" into a common index number.

In their statement to the House of Lords, the authors concentrated on describing their rating scheme rather than applying it to produce a list of strategic materials. They did select 15 materials to illustrate how the scheme would work. Two of the 15 materials were selected to show the independence of vulnerability and criticality. Fluorspar is critical for the production of aluminum and steel, but is mined in Great Britain and thus is not regarded as vulnerable. Vermiculite has high vulnerability because Great Britain is entirely dependent on imports from one dominant supplier (South Africa), but it is not critical because substitutes are readily available. Of the 13 other materials used to illustrate the IGS rating scheme, the authors said that most "are likely to manifest high degrees of both vulnerability and criticality, and would therefore be identified as strategically important." They are:

Aluminum
Columbium
Chromium
Cobalt
Manganese
Molybdenum
Nickel
Phosphate rock
Platinum-group metals
Tantalum
Tin
Tungsten
Vanadium

The materials selected are strategic to Great Britain but not necessarily to the United States. Molybdeum, for example, would not appear on a list of U.S. strategic materials because the United States is the world's largest producer and exporter and holds more than half of the world's resource base—a great deal more than any other country.

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[8] Institute of Geological Sciences, *Strategic Minerals*, Memorandum submitted to the Parliament, House of Lords. Select Committee on the European Community (Subcommittee F), Feb. 18, 1982.

A simpler scheme, based on the aggregate judgment of an expert panel, was used by the British Materials Forum on Strategic Materials.[9] Applying the concepts of degree of criticality and degree of vulnerability to the metals used by British industry, the forum reported that "the following group of eight metals emerged as meriting the highest priority in the newly defined strategic sense":[10]

Chromium
Cobalt
Columbium
Tungsten
Manganese
Vanadium
Molybdenum
Platinum-group metals

All members of the forum agreed on the rating, and all the metals were thought to merit equal rating. Again, the materials listed are strategic from the British point of view.

For each metal on the Materials Forum list, the criticality aspect was brought out by examining the metal's more important uses in key industries. To help assess vulnerability, the forum members looked at the ratio of reserves to production in each of the major producer countries of the world to estimate which countries are likely to become dominant in the future. The group recognized that the reserves-to-production ratio is a "static" indicator of reserve life (and could very well change as new reserves are discovered or as countries' rates of production change). The members used qualitative judgment, as well, in estimating probable future diversity of supply and in evaluating the political factors involved in vulnerability of supply.

The flavor of the forum's evaluation is suggested by the following excerpt from its discussion of chromium:[11]

> Although the physical long-term supply situation for the world as a whole looks reasonable . . .nevertheless, 97 percent of the presently known reserves of chromium are located in South Africa and adjacent Zimbabwe. The relatively small reserves located in other countries indicates that their present levels of production are unlikely to be maintained for more than 10 to 20 years (unless new reserves on a very substantial scale are found and then developed commercially within this time scale). Thus, along with many other consumer countries, the U.K. could steadily shift towards a greater dependence on South Africa and Zimbabwe for chromium supplies, whatever countries are supplying us at present. Since these two countries are surrounded by political uncertainties, or at least such is the generally accepted view by most Western countries, then imports to the U.K. need to be regarded as becoming increasingly "vulnerable" in the future.

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[9] The Materials Forum, *Strategic Metals and the United Kingdom*, cited in note 3.

[10] Ibid., p. 3.

[11] Ibid., p. 6.

APPENDIX B

Import Sources of Materials Judged to be Nonstrategic, 1978-82

1982 net import reliance	Commodity	Import sources (1978-81) by percent supplied	1982 consumption[a]
4	Aluminum	Canada(62), Ghana(11), Norway(4), Japan(4), Other(19)	4,740,000
45	Antimony	**Metal:** Bolivia(38), China(34), Mexico(10), Belgium-Luxembourg(7), Other(11)	33,200
		Ores and Concentrate: Bolivia(36), Canada(19), Mexico(19), Chile(8), Other(18)	
W[b]	Arsenic	Sweden(32), Mexico(30), France(25), Other(13)	W
74	Asbestos	Canada(97), South Africa(3)	267,300
52	Barite	China(24), Peru(21), Chile(13), Morocco(11), Other(31)	4,140,000
W	Bismuth	Mexico(29), Peru(26), Great Britain(13), West Germany(9), Other(23)	Reported: 1,050
69	Cadmium	**Metal:** Canada(27), Australia(18), Mexico(11), South Korea(9), Other(35)	4,087
3	Cement	Canada(49), Japan(15), Mexico(7), Spain(7), Other(22)	65,000,000
NA[c]	Cesium	**Compounds:** West Germany(95), Great Britain(4), Canada and France(1)	NA
		Pollucite: Canada(100)	
7	Copper	Chile(32), Canada(22), Peru(14), Zambia(11), Other(21)	1,980,000
100	Corundum	South Africa(100)	650
87	Fluorspar	Mexico(60), South Africa(30), Italy(4), Spain(3), Other(3)	800,000
61	Gallium	Switzerland(65), Canada(12), West Germany(10), China(6), Other(7)	Reported: 10
100	Gem stones	South Africa(29), Belgium-Luxembourg(23), Israel(21), India(11), Other(16)	$ million: 1,700
NA	Germanium	Belgium-Luxembourg(50), West Germany(12), China(12), Switzerland(11), Other(15)	46
43	Gold	Canada(52), Soviet Union(20), Switzerland(17), Other(11)	Troy oz: 3,800,000
36	Gypsum	Canada(73), Mexico(22), Spain(3), Other(2)	18,800,000
W	Hafnium	Negligible	Crystal bar: 50 Sponge: W
72	Ilmenite	Australia(59), Canada(34), South Africa(6), Other(1)	920,000
NA	Indium	Belgium-Luxembourg(32), Peru(28), Japan(11), Great Britain(9), Other(20)	NA
W	Iodine	Japan(81), Chile(18), Other(1)	3,950
36	Iron ore	Canada(64), Venezuela(16), Brazil(9), Liberia(7), Other(4)	61,150,000
22	Iron and steel	Europe(37), Japan(34), Canada(14), Other(15)	88,100,000
1	Lead	**Ore, concentrate and bullion:** Peru(32), Honduras(27), Canada(19), Australia(9), Other(13)	1,171,500
		Pigs and bars: Canada(39), Mexico(37), Peru(8), Australia(8), Other(8)	
2	Lime	Canada(94), Mexico(6)	14,900,000
43	Mercury	Spain(34), Japan(21), Italy(12), Algeria(10), Other(23)	76-lb flasks: 50,700
100	Mica sheet	India(83), Brazil(11), Madagascar(4), Other(2)	1,800
75	Nickel	Canada(44), Norway(11), Botswana(9), Australia(8), Other(28)	174,000

1982 net import reliance	Commodity	Import sources (1978-81) by percent supplied	1982 consumption[a]
9	Ammonia	Soviet Union(38), Canada(23), Mexico(21), Trinidad and Tobago(16), Other(2)	16,000,000
31	Peat	Canada(99), West Germany(1)	1,160,000
71	Potash	Canada(94), Israel(3), Other(3)	6,600,000
15	Pumice	Greece(87), Italy(13)	590,000
NA	Rare earths	**Monazite:** Australia(89), Malaysia(8), Thailand(3)	21,500
W	Rhenium	Chile(49), West Germany(47), Other(4)	Reported: 2.5
NA	Rubidium	Canada(100)	NA
8	Salt	Canada(38), Mexico(29), Bahamas(12), Other(21)	42,050,000
50	Selenium	Canada(44), Japan(17), West Germany(8), Great Britain(8), Other(23)	550
20	Silicon	Canada(25), Norway(22), Brazil(14), South Africa(7), Other(32)	330,000
59	Silver	Canada(37), Mexico(24), Peru(23), United Kingdom(5), Other(11)	Troy oz: 144,000,000
8	Sodium sulfate[d]	Canada(98), United Kingdom(1), Other(1)	1,278,000
100	Strontium	Mexico(99), Other(1)	15,000
3	Sulfur	Canada(58), Mexico(42)	11,440,000
W	Tellurium	Canada(43), Fiji(14), Hong Kong(13), Peru(9), Other(21)	85
W	Thallium	West Germany(81), Belgium-Luxembourg(9), Japan(6), Other(4)	W
NA	Thorium	France(80), Canada(6), Netherlands(6), Malta(3), Other(5)	15 (nonenergy)
12	Tit. dioxide	West Germany(31), Canada(14), Great Britain(13), France(12), Other(30)	721,000
48	Tungsten	Canada(21), Bolivia(19), China(14), Thailand(7), Other(39)	7,400
W	Yttrium	**Monazite:** Australia(89), Malaysia(8), Thailand(3) **Zenotime:** Malaysia, Australia **Yttrium concentrates:** Malaysia, Canada, Japan	140
53	Zinc	**Ore and concentrates:** Canada(59), Peru(17), Mexico(8), Other(16) **Metal:** Canada(51), Spain(8), Mexico(6), Australia(6), Other(16)	891,000
W	Zirconium	**Zirconium:** France(68), Japan(23), Canada(5), Other(4) **Zircon:** Australia(88), South Africa(10), Other(2)	Reported: 100,000

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[a] Statistics are for apparent consumption in short tons, except where indicated.

[b] W = withheld to avoid disclosing company proprietary data.

[c] NA = not available.

[d] 1982 import and consumption data is unavailable. 1981 data is reported here.

SOURCE: *1983 Mineral Commodity Summaries*, U.S. Department of the Interior, Bureau of Mines. All the data presented above contain 1982 statistics. The import sources are 4-year averages for the years 1978-81.

Appendix C

Overview of Second-Tier Materials

Bauxite and alumina are the raw and semiprocessed materials from which aluminum is made. They are considered to be strategic materials because of the high U.S. import reliance and because of the size and importance of the aluminum industry. For several reasons, however, bauxite and alumina are not in the first tier of strategic importance: many of the end uses of aluminum are not highly critical and can easily be replaced by substitute materials; the sources of bauxite and alumina supply are fairly diverse and relatively reliable; and, since the United States is the world's largest aluminum producer, accounting for 25 percent of the world's production of aluminum, the U.S. market is very important to foreign suppliers.

Alumina (aluminum oxide) is produced from bauxite, and it is made into aluminum for use in products such as alloys, chemicals, and abrasives. Aluminum alloys offer widely varying combinations of mechanical strength, ductility, electrical conductivity, and corrosion resistance. Some alloys have strengths approaching those of steel. Similar to most other materials, the worldwide recession caused declines in the consumption of bauxite and alumina in 1982 (see table C-1).

Containers and packaging account for over 20 percent of total aluminum consumption and are the largest end use for the material. Almost as large is the amount used in construction, for such products as residential siding, doors and windows, roofing, mobile homes, curtain walls, bridge rails, and guard rails. The automobile industry accounts for about 10 percent of U.S. aluminum consumption for such items as body, brakes, steering, pistons, trim, electrical uses, and metallic paint. Other transportation uses—marine vessels, rail cars, military vehicles, aircraft, and recreational vehicles—account for another 10 percent of consumption. Aluminum cable with steel reinforcing has replaced copper for high-capacity electrical transmission lines. This and other electrical uses account for still another 10 percent of the aluminum used in the United States.

Table C-1.—U.S. Consumption of Bauxite, 1978-82

Year	Apparent consumption (thousand metric dry tons)
1978	5,300
1979	5,106
1980	5,824
1981	5,555
1982	4,048

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

Approximately 10 percent of U.S. bauxite consumption goes into nonmetallic applications. Aluminous chemicals are used for water and sewage treatment, dyeing, leather tanning, and sizing paper. Bauxite is also used in high-alumina cement, as an absorbent or catalyst by the oil industry, in welding rod coatings, and in fluxes for steelmaking. High-alumina abrasives and refractories are used in glass and ceramic products.

For many of the important uses of aluminum there are adequate substitutes; e.g., steel and wood can be used in residential construction. Zinc-based diecastings and chromium-plated steel were replaced by aluminum in the automobile industry, and a shortage of aluminum could conceivably reverse this substitution. Copper can be used in electrical applications, and glass, plastics, paper, and steel can be used in packaging. For some transportation uses, magnesium and titanium can be used instead of aluminum, albeit at significantly increased costs.

Approximately 97 percent of U.S. bauxite supplies come from Jamaica, Guinea, and Suriname. Alumina is imported from Australia, Jamaica, and Suriname. Australia is the world's largest producer of bauxite. As table C-2 shows, many other countries have large reserves and production capacities of bauxite; e.g., Brazil, India, Guyana, Greece, and Yugoslavia. Thus, there is a wide diversity of world suppliers, each with large reserves.

The United States is the world's largest producer of aluminum and therefore the world's largest market for bauxite. It appears unlikely that raw materials producers would refuse sales to this country, lest they risk losing their share of this rich market.

The United States has a small bauxite mining industry, but reserves are relatively limited. The Bureau of Mines has conducted research on producing alumina from alternative materials such as clays, alunite (a potassium-aluminum-sulfur mineral), coal wastes, and oil shales. The United States has large resources of these materials and could meet most of its aluminum raw materials needs if the appropriate technology were developed. A private industry consortium, Alumet, has done work on producing alumina from domestic alunite. A large deposit of alunite discovered in Utah in 1970 could supply domestic aluminum producers for

Table C-2.—Bauxite: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1979-82):

Country	Percent
Jamaica	39
Guinea	32
Suriname	10

NOTE: 1982 U.S. net import reliance = 96 percent.

World mine production and reserves, 1982 (thousand metric dry tons):

	Mine production		Reserves	
Country	Amount	Percent	Amount	Percent
Australia	23,621	32	4,600,000	21
Guinea	10,908	15	5,900,000	26
Jamaica	8,380	11	2,000,000	9
Brazil	4,186	6	2,300,000	10
Soviet Union	4,600	6	300,000	1
Greece	2,853	4	650,000	3
Yugoslavia	3,668	5	400,000	2
Hungary	2,627	4	300,000	1
Suriname	3,059	4	600,000	3
India	1,854	2	1,200,000	5
Guyana	953	1	900,000	4
United States	732	1	40,000	<1
Other market economy countries	4,820	6	3,100,000	14
Other central economy countries	2,180	3	200,000	1
World total	74,441	100	22,500,000	100

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

years. But alunite is a lower grade alumina raw material than bauxite, and the processing is currently more expensive than the standard Bayer process used on bauxite. Although the technology is available (the Soviets are now producing alumina from alunite), it it uneconomic in the United States at this time.

Beryllium is the second tier because of its critical end uses and because one U.S. company is the sole processor of raw ore for beryllium in the entire free market world. Because of its relatively high price, use of beryllium is not widespread. But where it is used, it appears to be highly critical, especially to defense. Arguing against a higher strategic rank for beryllium is the fact that the United States is apparently capable of supplying most of its own needs. (U.S. production figures are not available, so this conclusion is not certain.) Also, beryllium is used in relatively small amounts, so transportation of imports is not a significant problem.

Forty percent of U.S. beryllium consumption goes to the aerospace industry and to nuclear weapons. Although the details of the military uses of beryllium are classified, beryllium is known to be a particularly good reflector of neutrons. Known aerospace applications have been in missiles, aircraft brake disks, aircraft frames, satellites and space vehicles, and inertial navigational systems for missiles and aircraft. Another large application (35 percent of consumption) is in beryllium-copper alloys in electronic components, including high-strength, noncorrosive housings for underwater cable repeater stations, contacts, and heat sinks. A relatively new use is in ceramic beryllium oxide substrates for complex electronic circuitry.

Consumption patterns of beryllium reflect its defense and aerospace uses. Table C-3 shows that consumption has actually been increasing, even in hard times.

Beryllium's special properties include light weight, high strength, high thermal conductivity, and neutron moderating and reflecting capability. There are some substitutes for beryllium metal (steel, titanium, graphite composites) and beryllium-

Table C-3.—U.S. Consumption of Beryllium, 1978-82

Year	Apparent consumption (short tons)
1978	271
1979	303
1980	321
1981	303
1982	150

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

copper alloys (phospher bronze), but not without a substantial loss of performance. Synthetic sapphire can be used in place of beryllium in some electronic uses.

Some beryllium ores are imported, but exact figures for net import reliance are not available because domestic production data are withheld to avoid disclosing company proprietary data (see table C-4). Before 1969, the United States was over 90 percent import-dependent. In that year, a domestic plant opened to convert imported and domestic beryl and bertrandite to to beryllium oxide. This plant is the only known ore processing facility in the market economy countries. It appears that the United States is capable of meeting its own beryllium requirements to a substantial degree. U.S. reserves are very large (28,000 tons) in relation to the 1982 consumption of 328 tons, and reported imports for 1982 were moderate—108 tons. Also, in the case of beryllium, distance from sources of supply is not an important factor. Because the material is used in relatively small quantities, it could be airlifted if necessary.

Columbium (niobium)[1] is included as a second-tier strategic material because it is entirely imported—mostly from a single source, Brazil—and because it is used in a variety of essential industries. It is not in the first tier, however, because there are a number of substitute materials. Also, it is used in limited quantities and could be airlifted from foreign suppliers if necessary. Table C-5 shows a trend of increased use of columbium, except for the recession year of 1982.

High-strength, low-alloy (HSLA) steels owe their strength and toughness in part to a fine-grained structure. Columbium is used in HSLA's at levels ranging from 0.01 to 0.04 percent by weight to help attain this structure. With the trend toward more use of HSLA steels to replace plain carbon steels, consumption of columbium has increased. The addition of ferro- and nickel-columbium to high-temperature superalloys imparts strength and carbide stability. For stainless steels, too, columbium provides carbide stability.[2] There are substitutes for columbium, but not without performance penalties; vanadium and molybdenum in HSLA steels; tantalum and titanium in stainless and high-strength steel and superalloys; molybdenum, tungsten, tantalum, and ceramics in high-temperature applica-

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[1] Columbium and niobium are two names for the same metal. The name columbium is favored by engineers and is generally used in describing the composition of alloys, while niobium is the accepted name in the scientific community. Since this report is directed toward engineering applications of strategic materials, the name columbium is used here.

[2] At high temperatures and pressure, molecular hydrogen dissociates into atomic hydrogen, penetrates steel (or other metals), and reacts with the carbon in the steel to form methane. This causes the metal to fail. This hydrogen attack is decreased with the addition of carbide stabilizers, such as chromium, molybdenum, tungsten, vanadium, and titanium as well as columbium.

Table C-4.—Beryllium: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1979-82):

Country	Percent
Brazil	38
China	40
South Africa	5
Rwanda	4
Other	13

NOTE: 1982 U.S. net import reliance = W.

World mine production and reserves, 1982 (short tons):

	Mine production		
Country	Amount	Percent	Reserves
Brazil	35	28	Not adequately delineated
South Africa	3	2	
Rwanda	4	3	
Argentina	1	1	
United States	W	NA	
China	NA	NA	
Other market economy countries	3	2	
Other central economy countries	80	63	
World total[a]	126	100	

[a] Does not include United States and China.
NA—Not applicable.
W—Withheld to avoid disclosing company proprietary data.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

Table C-5.—U.S. Consumption of Columbium, 1978-82

Year	Apparent consumption (short tons)
1978	3,293
1979	3,560
1980	3,767
1981	4,059
1982	3,300

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984.*

tions. Some of these substitutes are themselves considered strategic.

Columbium deposits exist in the United States, but none are producing, nor are they likely to in the near future. The United States imports all its columbium, either in the form of concentrates and tin slags or as ferrocolumbium. Brazil dominates U.S. imports and indeed world supplies. Its reserves will last for hundreds of years (see table C-6). The only other major source of U.S. imports is Canada, and its deposits are low-grade. A single overwhelmingly dominant source of supply makes for increased vulnerability even when the source is friendly and well-endowed with reserves.

Natural industrial diamonds are included as second-tier strategic materials because U.S. import dependence on them is 100 percent and because no substitutes are available. Another factor making for uncertain supply is that industrial diamond output depends largely on gemstone production and is not directly related to industrial diamond demand. Diamonds are not included in the first tier for two reasons: with the advent of a huge diamond industry in Australia, the western world's nearly complete reliance on African nations will disappear, and even from the limited area of southern Africa, supply has been quite reliable in the past. Table C-7 shows the trend in industrial diamond consumption in the United States.

The major use of industrial diamond stones is in drilling for minerals. Dies, core bits, cutting tool points, and electrical machinery also use natural diamond stone. Synthesized polycrystalline diamonds are competitive with natural stones in some applications where small stones are suitable, but synthesis of large industrial diamonds is not currently commercial. It is expected that eventually half of the demand for natural stones can be replaced by synthetics.

Although the United States currently mines no industrial diamond stones, there are diamond deposits near the Colorado-Wyoming border. The United States is the world's largest consumer of natural industrial diamond stones. As with several other strategic materials in the first and second tiers, supplies are limited to a rather small group of producers. Currently, the main sources of supply of natural stones are South Africa, Zaire, Belgium-Luxembourg, and Great Britain, as shown in

Table C-6.—Columbium: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1979-82):

Country	Percent
Brazil	75
Canada	6
Thailand	6
Other	13

NOTE: 1982 U.S. net import reliance = 100 percent.

World mine production and reserves, 1982 (short tons):

	Mine production		Reserves	
Country	Amount	Percent	Amount	Percent
Brazil	13,165	83	4,000,000	93
Canada	2,417	15	175,000	4
Nigeria	90	1	100,000	2
Zaire	10	<1	50,000	1
United States	Small	NA	Negligible	NA
Other market economy countries	98	1	9,500	0
Other central economy countries	NA	NA	NA	NA
World total	15,780	100	4,334,500	100

[a] Does not include United States or central economy countries.

NA—Not applicable.

W—Withheld to avoid disclosing company proprietary data.

NOTE: *American Metal Market* (Mar. 29, 1983) reports that China has 400 million metric tons of columbium-bearing iron ore. The Japanese are planning to extract the columbium during steelmaking.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984.*

Table C-7.—U.S. Consumption of Natural Industrial Diamond Stones, 1978-82

Year	Apparent consumption (million carats)
1978	3.7
1979	4.0
1980	3.4
1981	3.7
1982	2.9

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

table C-8. Australia is beginning full-scale production from its enormous reserves, with production expected to be about 2 million carats in 1983 and 15 million to 20 million carats in 1985, and could easily become the world's largest producer of industrial diamonds. Other countries with substantial, identified deposits are Ghana, Botswana, and the Soviet Union.

Natural graphite sources are well-diversified and its end uses are less critical as those for other materials considered here. Graphite is, however, considered strategic to some degree because of its wide-ranging uses and the many industries that employ it. Moreover, natural graphite comes in several forms, and certain uses require one particular form. Of these specific varieties, some are found in a very few places in the world. Because of its uses in the basic industries, demand for graphite has dropped with the 1982 recession, as shown in table C-9.

Of the many varieties of graphite (with distinctive characteristics and uses) the primary types are flake, lump, and amorphous. Amorphous is the cheapest, at $60 to $80/short ton, flake in the midrange at $200 to $1,000/short ton, and lump, the most expensive at $800 to $2,000/short ton. Natural graphite is used mainly to raise the carbon content in steel production. It is also used in refractories, for dressings and molds in foundry operations, and as lubricants. Because of its superior ability to conduct heat, crystalline flake is the only type of graphite used in crucibles.

Substitute and alternative materials do not perform as well as graphite for most applications. For example, in steelmaking, graphite goes into the metal more easily than do other sources of carbon because it does not emit as many volatiles. One significant functional substitution exists, however. Teflon and similar materials are increasingly used for bearings, so that the need for graphite lubricants for steel bearings has declined.

No natural graphite was produced domestically in 1982, although one deposit in Texas has been mined recently, and another in Alabama is being investigated. There are also deposits in Alaska, Idaho, Montana, New York, and Pennsylvania which are not economically viable at present.

Table C-8.—Natural Industrial Diamonds: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1979-82) (diamond stones):

Country	Percent
South Africa	60
Zaire	14
Belgium-Luxembourg	7
United Kingdom	7
Other	12

NOTE: 1982 U.S. net import reliance = 100 percent.

World mine production and reserves, 1982[a] (million carats):

Country	Mine production		Reserves	
	Amount	Percent	Amount	Percent
Soviet Union	8.5	25	80	8
Zaire	8.6	25	150	15
South Africa	5.8	17	70	7
Botswana	6.6	19	125	13
Ghana	0.6	2	15	2
Australia	0.5	1	500	50
China	1.6	4	20	2
Other market economy countries	2.4	7	30	3
World total	34.6	100	990	100

[a] Includes all natural industrial diamonds

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

Table C-9.—U.S. Consumption of Natural Graphite, 1978-82

Year	Apparent consumption (thousand short tons)
1978	W
1979	74
1980	49
1981	55
1982	43

W—Withheld to avoid disclosing company proprietary data.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

U.S. demand for graphite is met by imports of crystalline flake from Madagascar, lump and chip from Sri Lanka, and amorphous from Mexico. Korea, the Soviet Union, and China also export graphite to the United States. In general, reserves of graphite around the world are large and are not isolated in any particular geographic region, but specific types of graphite are highly localized. Table C-10 illustrates the U.S. imports, world production, and reserves.

Sri Lanka, sole world source for lump graphite, attempted to take advantage of the situation by escalating prices in the 1970s. This encouraged end-users to begin designing out requirement for lump graphite. As a result, Sri Lanka's market for its lump graphite is shrinking. It is this potential to substitute one type of graphite for another that puts graphite into the second tier of strategic materials.

Titanium and rutile are considered together here, because rutile is one of the ores from which titanium sponge (metal) is produced. Most rutile is consumed in the production of titanium dioxide pigment (see table C-11 for consumption statistics). Titanium has critical uses in certain industries—in particular, aerospace—and thus is strategic to some degree. It is not included in the first tier because the main sources of supply, of both rutile and titanium metal, are political allies of the United States and are considered secure suppliers. Also, substitutes do exist for many uses. Moreover, synthetic rutile can be produced from domestic ilmenite, another titaniferous ore.

U.S. consumption of titanium metal increased in recent years as the commercial and military aircraft fleets were built up, as shown in table C-12.

The major end use (60 percent) of titanium metal is in jet engines, airframes, and space and missile applications, where it is valued for its high strength and light weight. Another 20 percent of titanium consumed in the United States goes into steel and aluminum alloys, where titanium is used to remove oxygen and nitrogen and to toughen the alloys.

Table C-10.—Natural Graphite: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1979-82):

Country	Percent
Mexico	63
South Korea	4
Madagascar	6
China	8
Brazil	8
Other	12

NOTE: 1982 U.S. net import reliance = W.

World mine production and reserves, 1982[a] (thousand short tons):

	Mine production		Reserves
Country	Amount	Percent	Amount
South Korea	39	6	Large
India	49	8	Moderate
Mexico	38	6	Large
Austria	27	4	Large
Madagascar	11	2	Large
Sri Lanka	8	1	Moderate to large
United States	W	—	1,100
Other market economy countries	53	9	Moderate
Other central economy countries	383	63	Large
World total	608	100	170,000[a]

[a] This figure is from Bureau of Mines' statistics which aggregate reserves by continent.

W—Withheld to avoid disclosing company proprietary data.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

Table C-11.—U.S. Consumption of Rutile, 1978-82

Year	Reported consumption (short tons of concentrates)
1978	253,000
1979	314,000
1980	298,000
1981	285,000
1982	239,000

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*

Another 20 percent is used in the chemical processing industry, power generation,and marine and ordnance applications.

In some uses, high-nickel steel and superalloys can substitute for titanium alloys. For aircraft and space applications, high-strength, low-weight composite materials are being introduced to replace titanium. Also, new aluminum alloys produced by powder metallurgy techniques (discussed in ch. 7) provide alternatives to titanium in aerospace applications.

There is some rutile mining in the United States, but most of the material is imported (see table C-13). The major import source is Australia, with minor amounts coming from Sierra Leone and India. Brazil has by far the largest reserve base in the world, but current production there is limited. Sources of supply are quite diverse, with producers including Italy, South Africa, and Sri Lanka, as well as the other countries mentioned.

Ilmenite, a titaniferous ore which is abundant in this country, can be used to produce synthetic rutile, from which titanium can be made. A new synthetic rutile plant is being planned by a firm which mines ilmenite in Florida. The process to be used is the same as the one in current use in Australia. For most domestic producers of metal (mainly located on the west coast) it is cheaper to import rutile from Australia than to use synthetic rutile derived from domestic ilmenite. According to an industry source, the costs of starting up more synthetic rutile plants and shipping the produce to domestic sponge producers are the only barriers to U.S. self-sufficiency in titanium raw materials.

Major U.S. import sources for titanium sponge metal have been Japan, China, the Soviet Union, and Great Britain (see table C-14). The United States has enough processing capacity to produce all the titanium metal required for domestic consumption, but about 35 percent of capacity was idle in 1982.

Tantalum performs essential functions in certain products, and some of those products themselves meet critical needs. Others are nonessential. The present major U.S. import sources for tantalum are judged not to be highly reliable, which adds an element of risk. Yet worldwide ore production is quite substantial and diverse. For these combined rea-

Table C-12.—Rutile: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1979-82):

Country	Percent
Australia	69
South Africa	9
Sierra Leone	14
Other	8

NOTE: 1982 U.S. net import reliance = W

World mine production and reserves, 1982 (thousand short tons of concentrates):

Country	Mine production		Reserves	
	Amount	Percent	Amount	Percent
Australia	243	64	10,000	7
South Africa	52	14	7,000	5
Sierra Leone	53	14	4,000	3
Sri Lanka	14	4	6,000	4
India	9	2	4,000	3
United States	W	NA	3,000	2
Brazil	—	0	100,000	70
Italy	—	0	6,000	4
Central economy countries	10	3	3,000	2
World total	381[a]	100	143,000	100

[a] Excludes U.S. production.

NA—Not applicable.

W—Withheld to avoid disclosing company proprietary data.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

Table C-13.—U.S. Consumption of Titanium Sponge, 1978-82

Year	Reported consumption (short tons)
1978	19,854
1979	23,937
1980	26,943
1981	31,599
1982	17,328

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

sons, tantalum is in the second tier of strategic materials.

As indicated in table C-15, annual U.S. consumption of tantalum is small, on the order of 1 million pounds per year.

The largest share of U.S. tantalum consumption (54 percent) goes into electronic capacitors. Capacitors are used in all areas of electronics: computers and office equipment, telecommunications, instruments and controls, consumer, and automotive. Some areas of capacitor use may be considered essential and others not. For example, in the United States, consumer electronics accounts for about 12 percent of tantalum capacitors. (In Japan, by contrast, two-thirds of tantalum capacitors are used for this purpose.) Moreover, where size and stability are not essential features (as in consumer products), aluminum electrolytic capacitors are competitive and can substitute for tantalum capacitors. Thus, only a limited proportion of tantalum use in capacitors may be regarded as critical.

Another important use of tantalum (27 percent) is in cemented carbide metalworking tool bits. As an additive, tantalum carbide improves hot hardness and crater resistance in tool bits. Columbium carbide is a suitable substitute for the purpose. About 9 percent of tantalum consumption goes into high-temperature superalloys for critical parts (blades and vanes of gas-turbine engines for aircraft). The other principal use of tantalum is in mill products, mainly used by the chemical industry for such items as corrosion-resistant heat exchangers and tank linings. Substitute products are glass-lined containers, graphite, Hastelloy C, titanium, and zirconium.

The United States imports 90 percent of its tantalum in the form of concentrate and tin slags. The largest supplier is Thailand, with smaller amounts coming from Canada, Malaysia, and Brazil. Malaysia and Thailand ship substantial amounts of tantalum-containing tin slags, a source that is likely to decline as the old tin slags become depleted. Canada is the largest source of natural tantalum minerals, but Australia may eventually supply a larger portion. In addition, there are reserves of tantalum in Nigeria and Zaire. Nigeria's tantalum is a byproduct of columbium production; demand for Nigerian columbium may decline as production of columbium oxide in Brazil gears up. Nigerian tantalum production may then drop accordingly. Table C-16 contains statistics relating to tantalum.

No significant mining of tantalum has occurred in the United States since 1959. This country has 3.4 million pounds of tantalum resources in identified deposits, but they are uneconomic to develop at current prices. For several years world tantalum prices have been falling, which probably indicates confidence about future raw materials supply. As

Table C-14.—Titanium Sponge: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1979-82):

Country	Percent
Japan	85
China	11
Soviet Union	4

NOTE: 1982 U.S. net import reliance = W.

World mine production and reserves, 1982 (short tons):

Country	Mine production		Reserves	
	Amount	Percent	Amount	Percent
Soviet Union	44,000	53	50,000	39
United States	15,600	19	33,500	26
Japan	18,600	23	36,000	28
United Kingdom	2,600	3	5,500	4
China	1,500	2	3,000	2
World total	82,300	100	128,000	100

W—Withheld to avoid disclosing company proprietary data.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

Table C-15.—U.S. Consumption of Tantalum, 1978-82

Year	Apparent consumption (short tons)
1978	560
1979	720
1980	590
1981	630
1982	530

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

mentioned below, production capacities of developing nations for both tin and tantalum have been rising.

Tin is included in the second tier mainly bacause it occurs geologically with tantalum. Because of this geological pairing, tin supplies share characteristics of vulnerability with tantalum.

Tin consumption in the United States is shown in table C-17. Tin is used in cans and containers, electrical applications (solder), and in construction and transportation. Substitutions for most of these uses are widely available. There are a multitude of alternative materials for tin cans and containers. Epoxy resins can be used in place of solder in some nonelectrical uses, and aluminum or copper base alloys or plastics can be used in place of bronze. Lead-base bearing alloys and plastics can be used for tin-containing bearing metals as well. Thus, the essential use of tin is limited to electric solder. Nonetheless, because the material is pervasive in many industries, a serious interruption of supply might cause severe economic dislocation, until substitutes could be adopted.

The United States relies on imports for 72 percent of its tin requirements. Major import sources at present are Malaysia, Thailand, Bolivia, and Indonesia. Quite a few other countries have large deposits (China, Soviet Union, Burma, Brazil, Australia, Nigeria, the United Kingdom, and Zaire), as shown in table C-18. In the developed world, a British mining consortium is going ahead with the first commercial use of a suction dredge for the seabed mining of tin in sands off the coast of Cornwall.

Small quantities of tin are produced domestically, as a byproduct of molybdenum mining in Colorado, and from placer deposits in Alaska and New Mexico. Over 20 percent of the tin consumed in this country comes from recycled scrap.

There is a large inventory of tin in the U.S. stockpile, which essentially serves as another supply source, since sales are made constantly to reduce the surplus. From July 1980, when tin sales began, to the end of 1982, over 10,467 tonnes of tin were disposed of from the stockpile. This amounted to approximately 7 percent of U.S. apparent consumption over that period.

Vanadium is on the second-tier list because of its critical uses. It is employed in a variety of steel and

Table C-16.—Tantalum: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1979-82):

Country	Percent
Thailand	42
Canada	11
Malaysia	9
Brazil	8
Other	30

NOTE: 1982 U.S. net import reliance = 92 percent.

World mine production and reserves, 1982 (short tons):

Country	Mine production Amount	Mine production Percent	Reserves Amount	Reserves Percent
Brazil	115	31	1,500	4
Canada	85	23	3,000	9
Australia	85	23	7,500	22
Thailand	10	3	10,000	29
Nigeria	12	3	5,000	15
Zaire	10	3	3,000	9
Malaysia	—	0	2,000	6
Mozambique	NA	NA	NA	NA
Other market economy countries	50	14	2,000	6
Other central economy countries	NA	NA	NA	NA
World total	367	100	34,000	100

NA—Not applicable.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984*.

Table C-17.—U.S. Consumption of Tin, 1978-82

Year	Apparent consumption (short tons)
1978	70,304
1979	76,262
1980	60,068
1981	60,012
1982	44,364

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984.*

alloy products and as a chemical catalyst. Of the possible substitutes for vanadium, many are themselves more strategic. U.S. vanadium supplies and processing capacity are sufficient to meet this country's requirements. Yet a considerable amount is being imported at present, which adds an element of vulnerability. Altogether, vanadium probably belongs near the bottom of the list of second-tier strategic materials.

Vanadium is another material that is used in comparatively small quantities, as shown in table C-19. About 80 percent of the U.S. vanadium consumption is used as a microalloying agent in steelmaking. Vanadium imparts hardening properties to steel by means of grain refinement. It is used in high-speed tool steels and high-temperature rotors because it forms stable carbides and resists high-temperature abrasion. It is used in crankshafts, pinions, and gears because of its shock and wear resistance. The high strength-to-weight ratios of steels containing vanadium (HSLA and full-alloy steels) make these steels valuable in weight-saving components. Because of its various uses in steel products, demand for vanadium is tied to the demand for steel.

Ten percent of U.S. vanadium demand is in titanium alloys, where it provides strength and workability. The rest of U.S. vanadium consumption is in the chemical industry, where vanadium is used as a catalyst, mainly in the production of sulfuric acid.

Many metals are interchangeable with vanadium to some degree in alloying; examples are columbium, molybdenum, manganese, titanium, and tungsten. Platinum can be used in place of vanadium as a catalyst in the chemical industry.

Table C-18.—Tin: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1978-81):

Country	Percent
Malaysia	39
Thailand	21
Bolivia	17
Indonesia	13
Other	10

NOTE: 1982 U.S. net import reliance = 72 percent.

World mine production and reserves, 1982 (short tons):

	Mine production		Reserves	
Country	Amount	Percent	Amount	Percent
Malaysia	57,600	22	1,320,000	12
Soviet Union	40,800	15	1,100,000	10
Indonesia	40,200	15	1,705,000	16
Thailand	28,700	11	1,320,000	12
Bolivia	29,500	11	1,080,000	10
China	16,500	6	1,650,000	15
Australia	14,000	5	385,000	4
Brazil	10,500	4	440,000	4
Great Britain	4,400	2	286,000	3
Zaire	2,400	1	220,000	2
Nigeria	3,000	1	308,000	3
Burma	1,900	1	550,000	5
United States	Negligible	—	77,000	1
Other market economy countries	12,100	5	231,000	2
Other central economy countries	4,000	2	66,000	1
World total	265,600[a]	100	10,738,000	100

[a] Excludes U.S. production.

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984.*

Table C-19.—U.S. Consumption of Vanadium, 1978-82

Year	Apparent consumption (short tons)
1978	8,164
1979	10,168
1980	8,521
1981	9,584
1982	6,406

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984.*

Overall, U.S. net import reliance for vanadium (24 percent) is not as high as for most other strategic materials, but this is due in part to the depressed state of the steel industry in 1982. The foreign sources of supply are not very diverse; the majority of vanadium imports originate in South Africa, as table C-20 indicates. The major world deposits are located in South Africa, the Soviet Union, the United States, and China. These same countries are the world's leading producers of vanadium. In this country, vanadium is usually mined as a coproduct or byproduct of uranium or phosphorus; an exception is the vanadium mine in Hot Springs, Arkansas. Because of this geological pairing, continued U.S. production may be somewhat uncertain, since it depends to a considerable degree on the market for unrelated minerals. Although the United States has the reserves to be self-sufficient, market forces may at times favor imports.

Vanadium can also be recovered from iron slags and petroleum residues. Japan and the United States are the only countries currently producing vanadium from petroleum. The United States uses Venezuelan crude oil as a vanadium resource.

Vanadium is also imported in semiprocesed form as ferrovanadium, largely from industrialized countries. Canada, Belgium, Luxembourg, and West Germany supply approximately 90 percent of U.S. ferrovanadium imports. Canada processes U.S. and South African ores into ferrovanadium and then exports it to this country.

Table C-20.—Vanadium: U.S. Imports, World Production, and Reserves

Sources of U.S. imports (1979-82):

Country	Percent
South Africa	54
Canada	10
Finland	7
Other	29

NOTE: 1982 U.S. net import reliance = 24 percent.

World mine production and reserves, 1982 (short tons):

Country	Mine production		Reserves	
	Amount	Percent	Amount	Percent
South Africa	13,200	36	8,600,000	47
Soviet Union	10,500	29	4,500,000	25
China	5,000	14	1,800,000	10
United States	4,100	11	2,400,000	13
Finland	3,470	10	100,000	1
Australia	110	<1	270,000	1
Other market economy countries	120	<1	600,000	3
World total	36,500	100	18,250,000	100

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries 1984.*

This appendix draws on information contained in the U.S. Bureau of Mines publications *Mineral Commodity Summaries 1983, Mineral Facts and Problems 1980,* and issues of *Mineral Commodity Profiles 1983* for the specified metals.

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